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SATELLITE CONSTELLATIONS FOR WORLDWIDE AND HEMISPHERE COVERAGE

L. N. Rowell

A Rand Note
prepared for the
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N-1432-DCA   Satellite Constellations for
  Worldwide and Hemisphere Coverage.*
  L. N. Rowell. December 1979.

Continuous earth-to-space communications
require that at least one satellite be in
view of the ground station at all times.
The satellite constellations discussed in
this note are designed to maximize the
probability that one or more of the satel-
lites in the constellation will always be
at an elevation angle of 20 degrees or more
above the horizon of the ground station.
(This maximum elevation angle is based on
the assumption that millimeter waves will
be used for communication.) Constellations
of satellites in circular orbits at syn-
chronous and five times synchronous alti-
tude and also in elliptical orbits are
presented. Some of the constellations are
designed to maximize global coverage (i.e.,
a ground station located anywhere on earth)
and others are designed to maximize cover-
age for the northern hemisphere. 48 pp.
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(10) L. N./Rowell

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PREFACE

This Rand Note was prepared for the Military Satellite Communications System Office (MSO) of the Defense Communications Agency (DCA) as one of three parts of the final report on a study entitled "Investigation of Millimeter Band for MILSATCOM Applications." The work discussed here is a follow-on to a prior study for DCA (see Rand Report R-2275-DCA, *The Feasibility of Employing Frequencies between 20 and 300 GHz for Earth-Satellite Communications Links*, May 1978). It presents satellite constellations that provide both worldwide and hemisphere coverage—that is, constellations that ensure with high probability that one or more satellites are continuously in view of earth-based users.

The information contained in this Note should be useful to designers of future communications satellite systems.

SUMMARY

This Note discusses satellite constellations at synchronous altitude (about 20,000 n mi) and 5 x synchronous altitude that keep one or more satellites in view from the ground at elevation angles above 20° or 30°. A prior Rand study[*] recognized that the performance of high frequency (above 20 GHz) communication systems degrades significantly at low elevation angles because of atmospheric attenuation. Therefore, the minimum elevation angle at the user was set at 20°. This same elevation angle constraint was retained for this study. The results presented here show that at least 10 satellites (4 Defense Satellite Communication System satellites (DSCS) plus 6 additional satellites in inclined, circular orbits) are needed to obtain worldwide coverage. Also, at least 9 satellites in inclined, elliptical orbits are required for hemispheric coverage. The DSCS satellites are included because it is assumed that they will be an integral part of future communication systems. A follow-on study is being done at Rand to determine the desirability and performance implications of employing user elevation angles below 20°. The relaxation of this elevation angle constraint will reduce the number of satellites required.

Worldwide coverage (i.e., one or more satellites in view of a user located anywhere on earth) is achieved by using hybrid constellations that include satellites in circular, equatorial orbits. This mixture of orbit plane inclinations minimizes the number of satellites required for 100 percent coverage.

Hemisphere coverage is best achieved with constellations of satellites in equally inclined, elliptical orbits. If the orbits

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[*] Mundie, L. G. and N. E. Feldman, *The Feasibility of Employing Frequencies between 20 and 30 GHz for Earth-Satellite Communications Links*, The Rand Corporation, R-2275-DCA, May 1978.

are inclined 63.4° (at this inclination the location of orbital apogee remains fixed) and the position of orbital apogee is also at high latitude, the number of satellites required to give complete coverage is minimized. Thus for this analysis, the orbital apogee is located at 63.4° in the hemisphere of interest.

The changes in coverage and coverage redundancy (two or more satellites in view of a user) caused by varying the constellation parameters and orbital parameters are examined.

ACKNOWLEDGMENTS

CONTENTS

I. INTRODUCTION

This Rand Note describes satellite constellations that will
keep one or more communications satellites in view of an earth-based
user for a fraction of the time to 100 percent of the time. Also
described is the effect on coverage (percent of the time that one or
more satellites are in view) that is caused by varying the parameters
of both the constellation and the orbits.

The primary objective is to design satellite constellations that
give continuous worldwide or hemisphere coverage subject to the con-
straints that the elevation angles of the satellites, measured at
the user, be 20° or more and that the altitude of the constellation
not exceed 100,000 n mi (5 x sync altitude).[*] This objective was
achieved by varying the parameters of both constellations and orbits
in computer simulations to show the geographical extent of space to
ground communications link coverage.[**]

The following table summarizes the constellations that were
simulated.

	Constellation	Number of Orbit Planes	Number of Satellites	Satellite Altitude (n mi)
A	DSCS	1	4	Sync (Eq)
B	Supplemented DSCS	4, 5, 7	10, 13, 16	0.63, 1, 5 x sync
C	Elliptical Orbits	3	6, 9	Sync, 5 x sync (Apogee Altitude)
D	Circular Eq. + Elliptical Orbits	1-3	4-6	Sync

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[*]High elevation angles are desirable for communication systems
using the higher frequencies of 30/20, 43-45, or 51/41 GHz (see foot-
note, p. v). Synchronous altitude is about 20,000 n mi and the orbital
period is 24 hours. At altitudes exceeding 100,000 n mi orbital per-
turbations caused by the moon may be significant.

[**]The simulations use an Aerospace Corporation computer program
that was modified for our use (see Lamar, J. V., L. N. Rowell and
J. J. Mate, *Geometric Performance of Pseudoranging Navigation Satellite
Systems: A Computer Program*, The Rand Corporation, R-1949-AF, July
1977).

The four DSCS satellites (A) and their orbit plane are included in the number of orbit planes and in the number of satellites.

There are four DSCS satellites at synchronous altitude in the equatorial plane. In order to obtain worldwide coverage they were supplemented with six to twelve additional satellites in inclined, circular orbits (B).

Elliptical orbit constellations (C) were used to obtain hemisphere or high-latitude coverage. The orbital eccentricities were 0.43, 0.63, and 0.83 and orbital apogee was located at the latitude equal to the orbit plane inclination, i.e., at the northernmost (or southernmost) latitude of satellite travel.

Finally, constellations (D) consisting of satellites in elliptical inclined orbits and in circular equatorial orbits were used to obtain hemisphere coverage plus additional equatorial region coverage.

The following constellation parameters were varied:

- Initial longitude relative to DSCS
- Initial position of the satellites in the orbit planes
- Initial phasing of the satellites between planes
- The total number of satellites
- The number of orbit planes

The approximate longitudes of the four DSCS satellites are 60°E, 175°E, 135°W, and 13°W. The initial relative longitude of the constellation used to supplement DSCS was varied to obtain the maximum coverage.

The initial position of the first satellite in the first orbit plane was varied, with the other satellites in the plane spaced uniformly, until coverage was maximized.

For the circular-orbit constellations used to supplement the DSCS, the position of the first satellite in the second orbit plane was displaced in-plane relative to the position of the first satellite in the first orbit plane by a central angle equal to 360° divided by the total number of satellites in the constellation supplementing the

DSCS. The first satellite in the third plane was moved in-plane by an angle equal to 2 x 360° divided by the total number of satellites, etc. For the constellations consisting of elliptical orbits, the same procedure was followed except the orbital period was divided by the total number of satellites and these times were used to compute the in-plane angular displacement of the satellites from orbital perigee.

The total number of satellites in the constellation (B) supplementing the DSCS were divided equally among the orbit planes which ranged from three to six in addition to the DSCS plane, and the planes were uniformly distributed in longitude.

The following orbit parameters were varied:

- Altitude (period)
- Inclination
- Eccentricity

The circular orbit altitudes were 0.63 sync, sync, and 5 x sync which correspond to altitudes of 10,924 n mi, 19,364 n mi, and 99,760 n mi, respectively. The corresponding orbital periods were 12 hours, 24 hours, and 231 hours (9.63 days).

The orbital plane inclinations examined were 45°, 55°, 63.4°, and 70°. The orbital eccentricities were 0.43, 0.63, and 0.83.

Section II presents the coverage that can be obtained using only the DSCS (constellation A).

Section III shows the worldwide coverage that can be obtained using constellations of satellites in inclined, circular orbits plus the DSCS (B). (Also, the effect of both constellation and orbit parameter variations on coverag is discussed.)

Section IV shows the hemisphere coverage that can be obtained using constellations consisting of satellites in inclined elliptical orbits (C).

Section V shows that coverage of the equatorial region can be added to the hemisphere coverage (which is obtained using elliptical

orbits) by adding synchronous, equatorial satellites in circular
orbits (D).

Appendix A discusses the coverage effects caused by varying the
parameters of the constellation.

Appendix B discusses the effects on coverage and coverage re-
dundancy of varying the parameters of the satellite orbits and con-
stellations.

II.   COVERAGE USING THE DEFENSE SATELLITE COMMUNICATION SYSTEM (DSCS)

The four DSCS satellites are in circular synchronous, equatorial orbits. They are located at the approximate longitudes 60°E, 175°E, 135°W, and 13°W as shown in Fig. 1. Coverage patterns for user elevation angles of 0° and 30° are shown. For 0° elevation angle, earth-based users at latitudes up to about 72° can always see at least one satellite, and two satellites in some areas (Fig. 1). However, if the elevation angle must be 30° or more, then there is about 93 percent coverage at the equator and no coverage above 52° latitude.

Figure 2 shows the probability of one or more DSCS satellites above specified elevation angles as a function of user position (latitude and randomly chosen longitude). If the elevation angle of 20° is the minimum acceptable angle, then DSCS provides 100 percent coverage at any longitude for latitudes up to 20 degrees.[*]

Figure 3 shows the probabilities of seeing one or more or two or more DSCS satellites above 0° and 30° elevation angles. The probability of seeing two DSCS satellites for 30° elevation angle is at most about 25 percent at the equator. This means that if one satellite fails the operational capability of the DSCS degrades significantly in regions not having redundant coverage.

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[*] For Fig. 2 and all other figures showing coverage probability, the data points are computed for every 10° of latitude. The connecting lines are added for clarity.
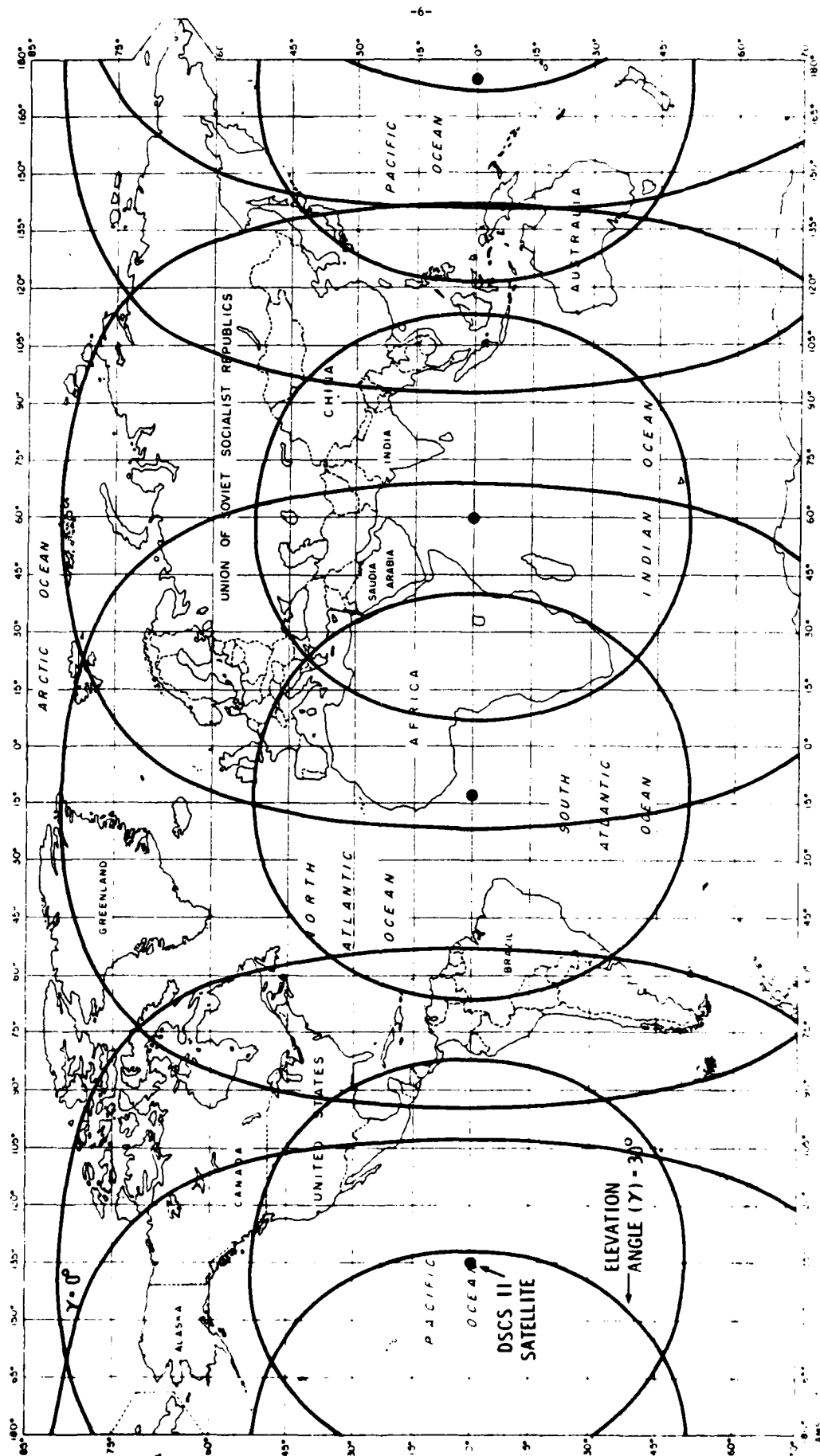
Fig. 1— WORLD-WIDE LINE-OF-SIGHT COVERAGE PATTERN USING 4 GEOSYNCHRONOUS SATELLITES
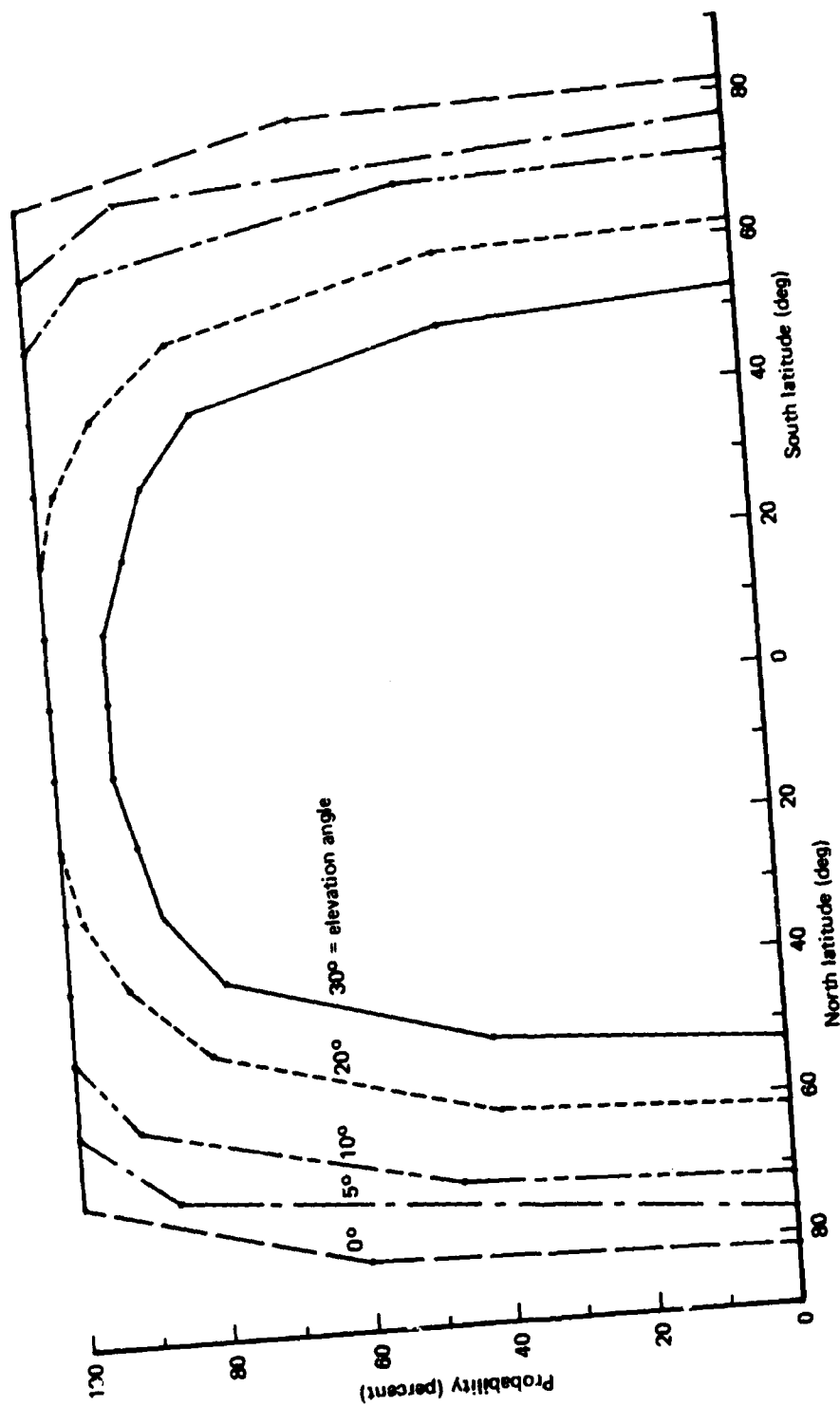
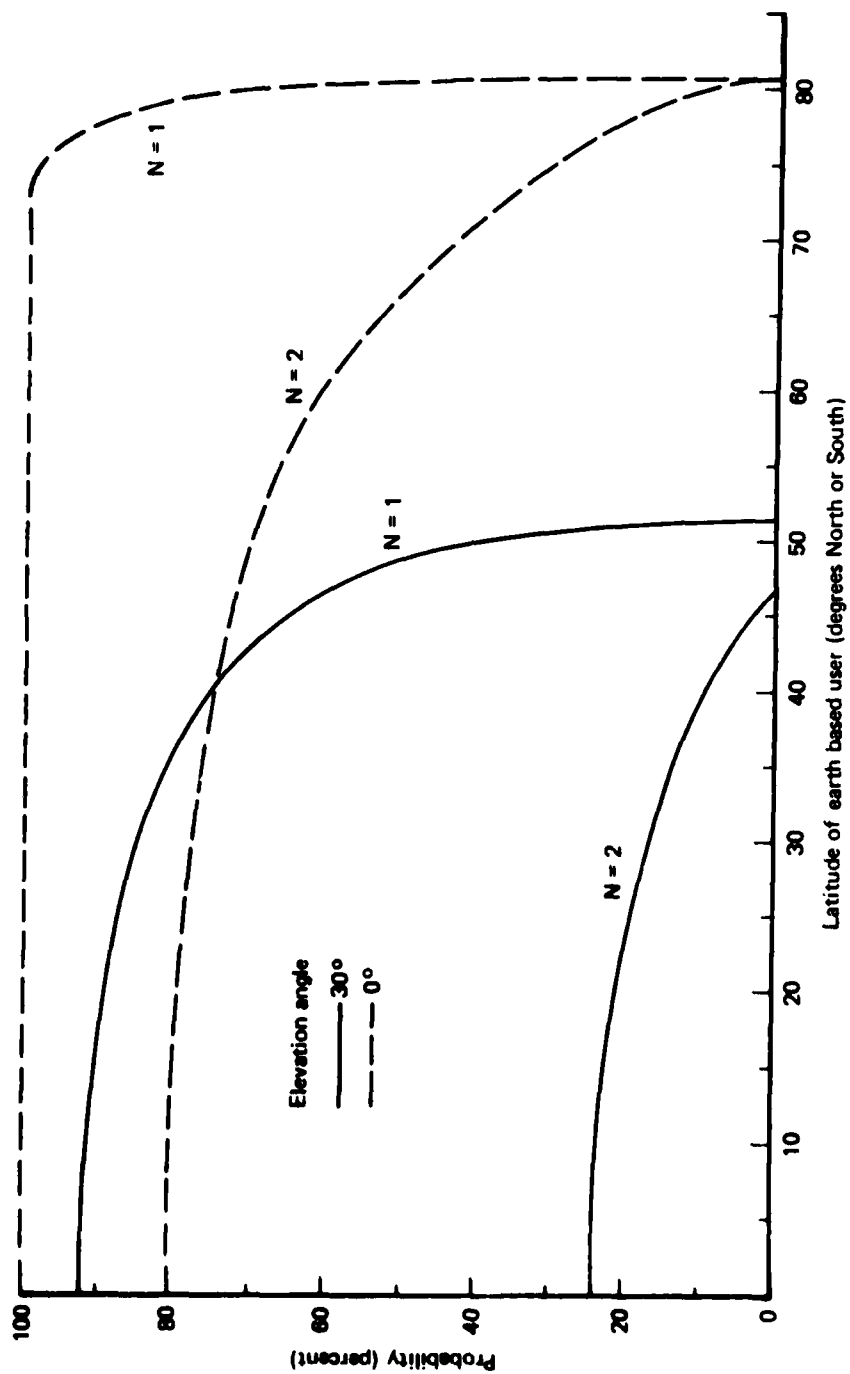Fig. 2—Probability of one or more satellites above elevation angle using DSCS

-8-

Fig. 3—Probability of seeing N or more of DSCS: parameter user elevation angle

III. WORLDWIDE COVERAGE USING CIRCULAR ORBIT SATELLITE CONSTELLATIONS WHICH INCLUDE DSCS

At certain longitude locations none of the DSCS satellites (constellation A) are in view at 30° elevation angle or above. This is caused by the unequal longitude spacing of the DSCS. If they were equally spaced in longitude (every 90°), then one or more of them would be at or above 30° elevation angle to an earth-based user as far north (or south) as about 30°. The loss of coverage caused by the unequal longitude spacing of the DSCS becomes insignificant when the DSCS is supplemented with constellations that give nearly worldwide coverage, as will be shown.

Figure 4 illustrates a typical constellation B satellite arrangement. The DSCS orbits are supplemented by three inclined circular orbits that contain nine additional satellites with three satellites per plane separated 120° in-plane.

By varying the parameters of both the constellations and the orbits and then doing a computer simulation of the motion of the satellites, constellations were found which give complete coverage while minimizing the total number of satellites or the total number of orbit planes.

The best constellations and the levels of coverage that were obtained by varying the parameters are shown in Figs. 5-11. Detailed results that show the change in coverage caused by varying both the constellation and orbit parameters are included in the Appendixes.

Each of the four constellations in Fig. 5[*] contains six satellites in addition to the four DSCS satellites. The orbits of all four are inclined 63.4° to the equator. The constellations associated with curves A and B contain six orbit planes (one satellite per plane) equally spaced in longitude. Curves C and D correspond to constellations having three planes equally spaced in longitude with two

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[*]The lack of symmetry of the coverage about 0° latitude is caused by using an integration step size that is too large.
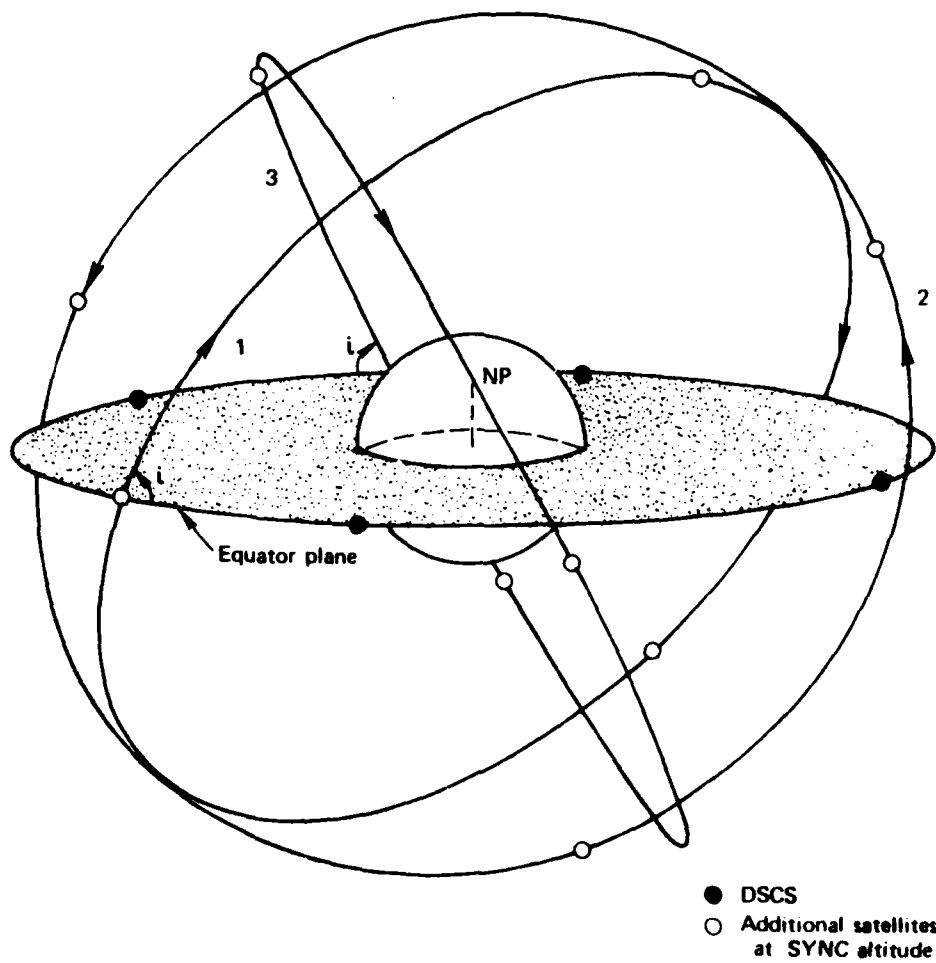
Fig. 4 — DSCS plus nine satellites in three circular, inclined orbits
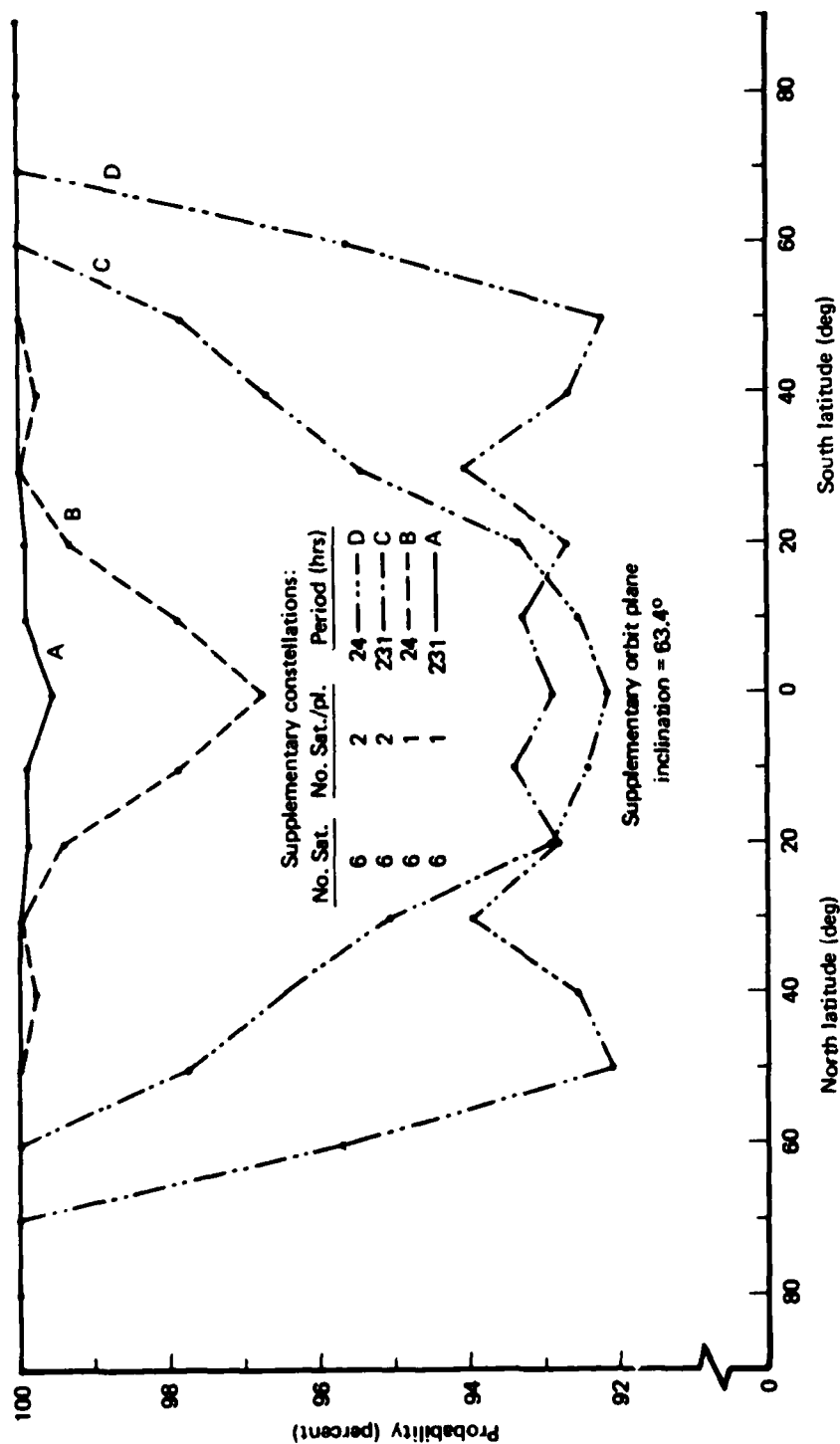
Fig. 5—Probability of one or more satellites above 30° elevation angle for constellations including 4 DSCS: 10 satellites total

satellites per plane. Curves B and D correspond to orbits at synchro-
nous altitude. The better coverage shown by curve B results from
increasing the number of orbit planes from three to six. Curves A
and C correspond to constellations at 5 x synchronous altitude and,
again, the better coverage shown by curve A is a result of doubling
the number of orbit planes. For either number of orbit planes, the
coverage is improved by raising the altitude of the constellations
from synchronous to 5 x synchronous altitude.

The coverage shown by curve A probably could be further improved
to 100 percent if fine adjustments of the constellation parameters
are made.

Coverage redundancy is assessed as the probability that two or
more satellites are in view of an earth-based user. A high level of
redundancy simply means that the communication link can with high
probability be maintained if one satellite fails.

If continuous coverage is essential then the additional number
of satellites or orbit planes needed for a high level of coverage
redundancy may be justified on the basis of costs.[*]

Figure 6 shows the probability that two or more satellites are
in view. Except for latitudes near the equator ($\pm$ 15°), the six
orbit plane constellations give the greatest coverage redundancy.
Note that the probability of two or more satellites in view, for all
latitudes, is 50 percent or better for curve A.

The coverage for a user elevation angle of 20°[**] is shown in
Figs. 7 and 8 for the same constellation as in Figs. 5 and 6, re-
spectively. Both the level of coverage (compare Figs. 5 and 7) and
the level of coverage redundancy (compare Figs. 6 and 8) are sig-
nificantly improved by reducing the minimum elevation to 20°. Note
that the coverage is now 100 percent for the constellation at synchro-
nous altitude (as well as at 5 x synchronous altitude) if the

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[*]The costs for continuously available backup satellites in orbit
may be much less than the cost of maintaining spares and facilities
in a state of readiness to launch replacements.

[**]As the elevation angle is reduced the atmospheric attenuation
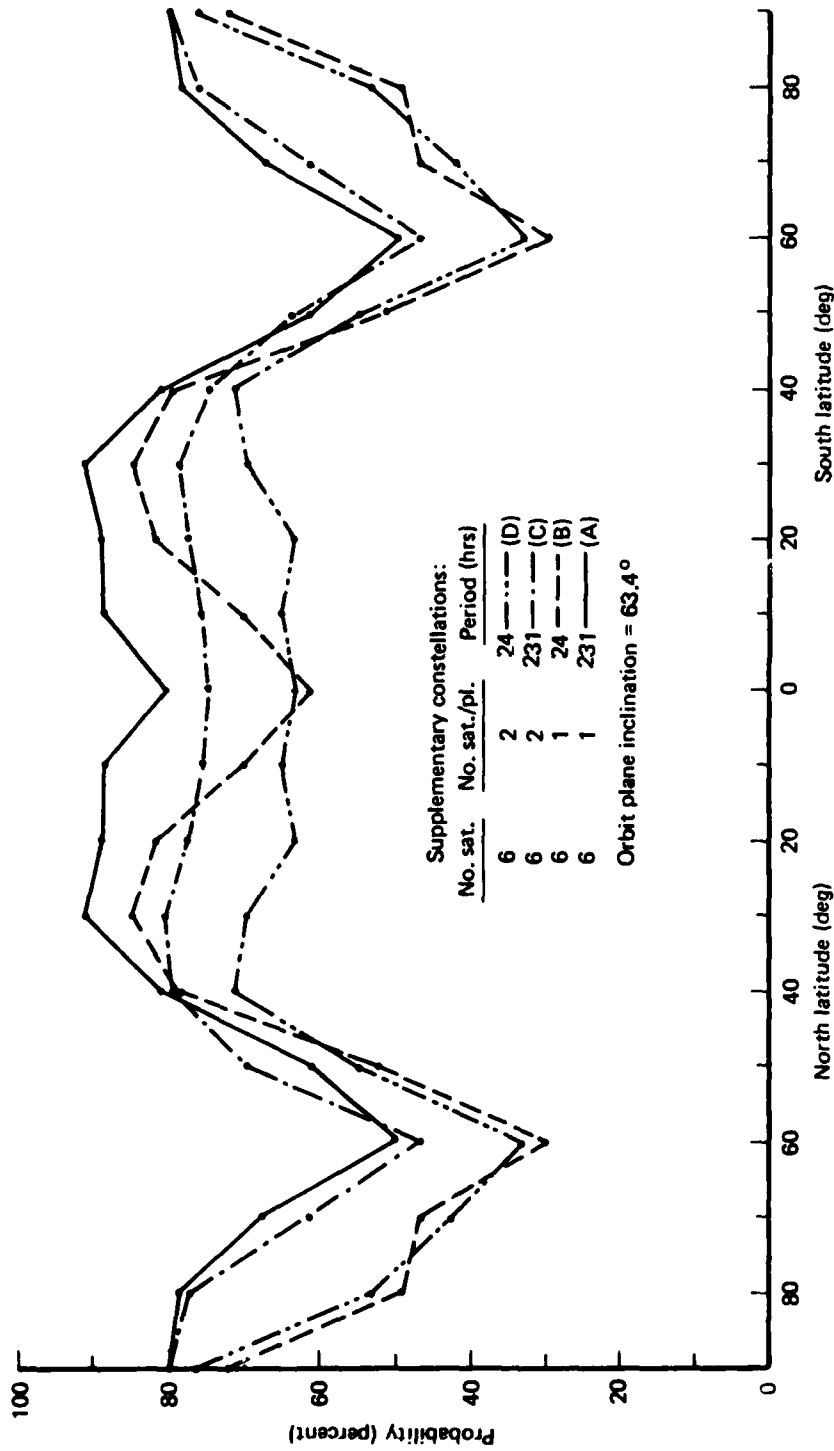of line-of-sight radio transmissions increases.

Fig. 6—Probability of two or more satellites above 30° elevation angle for constellations including 4 DSCS: 10 satellites total
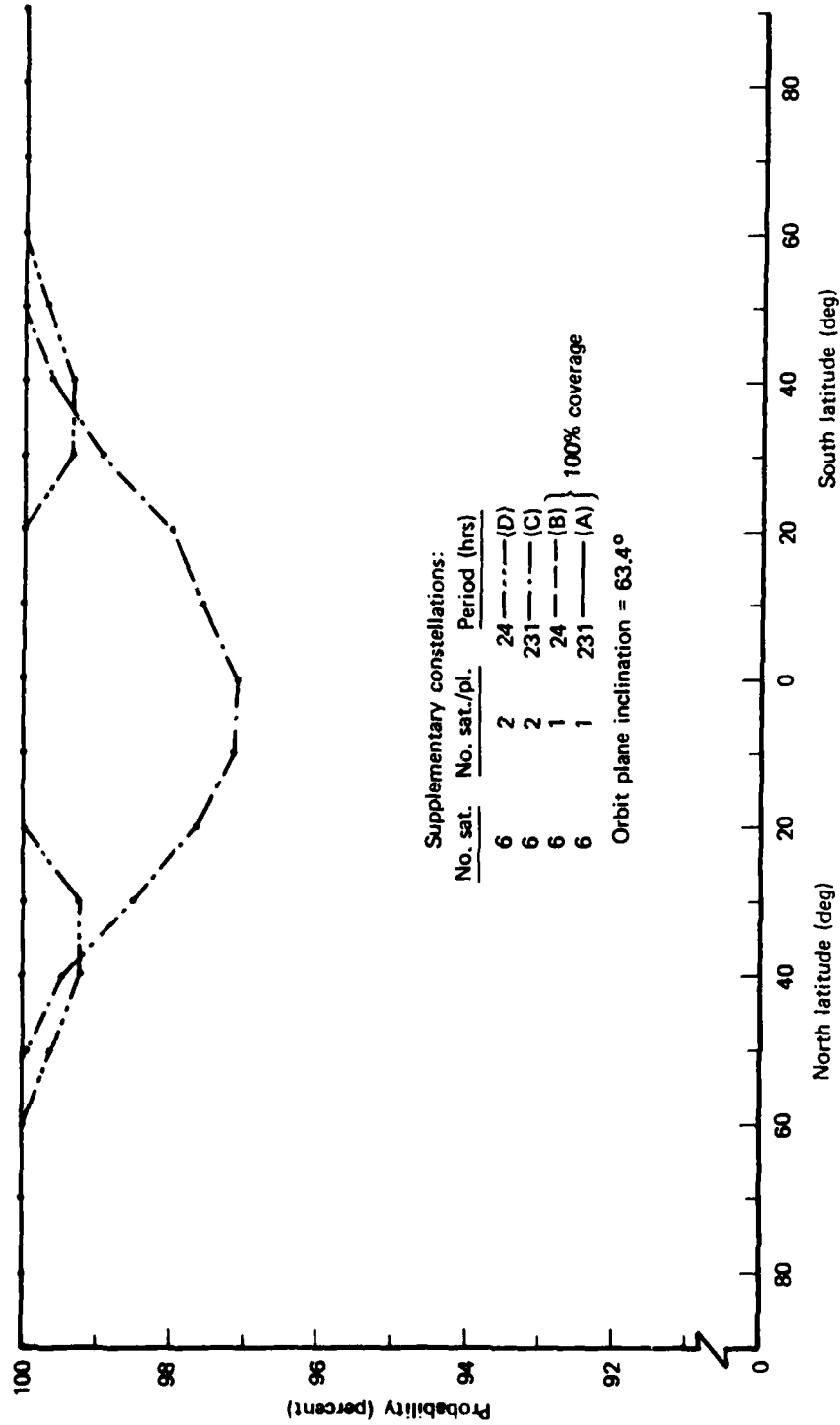
Fig. 7—Probability of one or more satellites above 20° elevation angle for constellations including 4 DSCS: 10 satellites total.
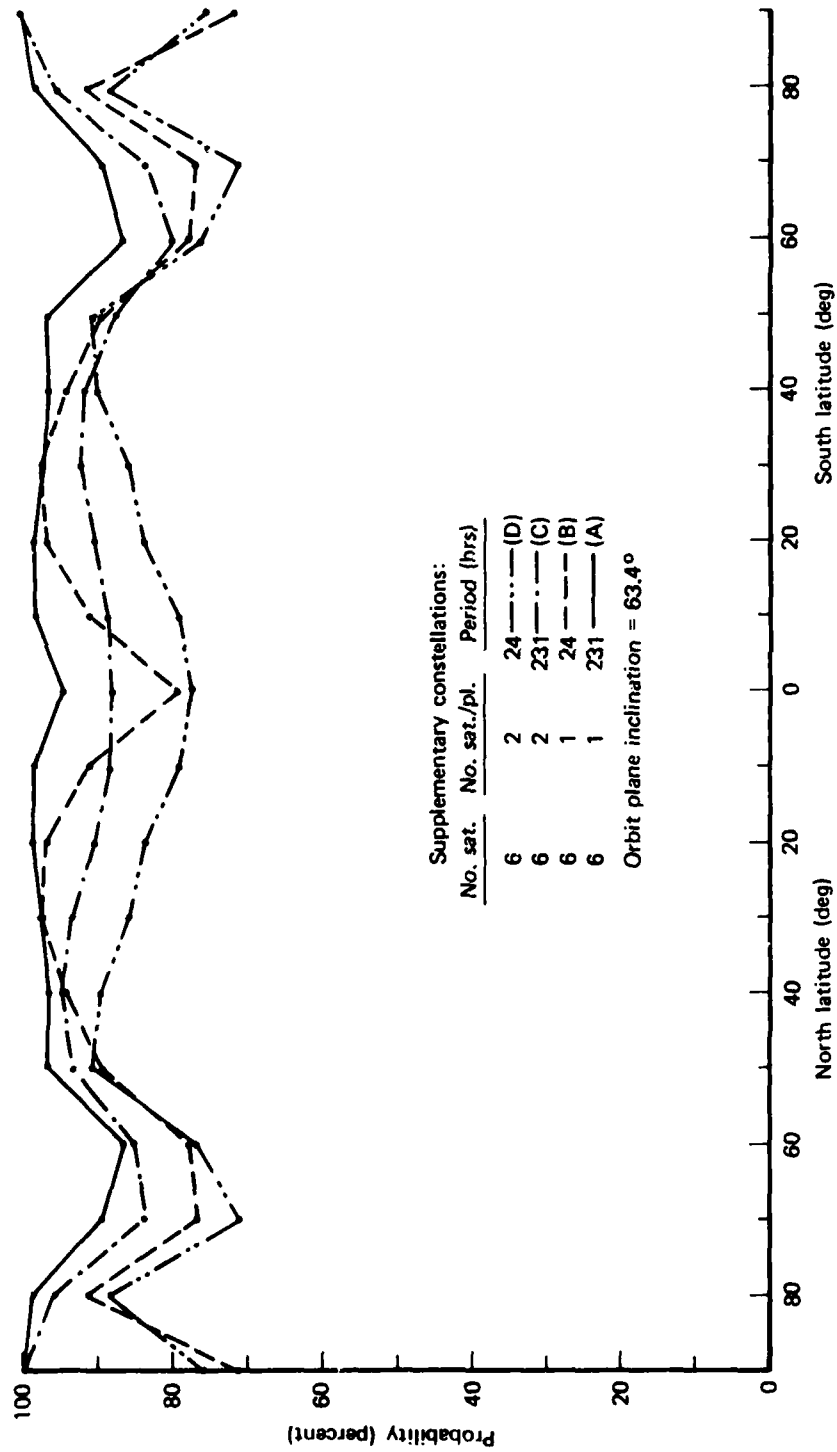
Fig. 8—Probability of two or more satellites above 20° elevation angle for constellations including 4 DSCS: 10 satellites total

satellites are in six planes (curve B, Fig. 7). Also, the coverage redundancy is above 75 percent for both altitudes (curves A and B, Fig. 8).

The coverage that can be obtained if three more satellites are added to the supplementary constellations is shown in Figs. 9-11. These added satellites increase the coverage by 6 percent at low and middle latitudes (compare Figs. 5 and 9). This improvement in coverage redundancy ranges from 10 to 45 percent (compare Figs. 6 and 10).

If the elevation angle at the user is reduced from 30° to 20° all of the above constellations give 100 percent coverage and the coverage redundancy (see Fig. 11) is 100 percent for all constellations except the one associated with curve D--and for it the coverage redundancy exceeds 97 percent for all latitudes. The minimum coverage redundancy achieved using supplementary constellations containing six satellites is about 71 percent (see Fig. 8).

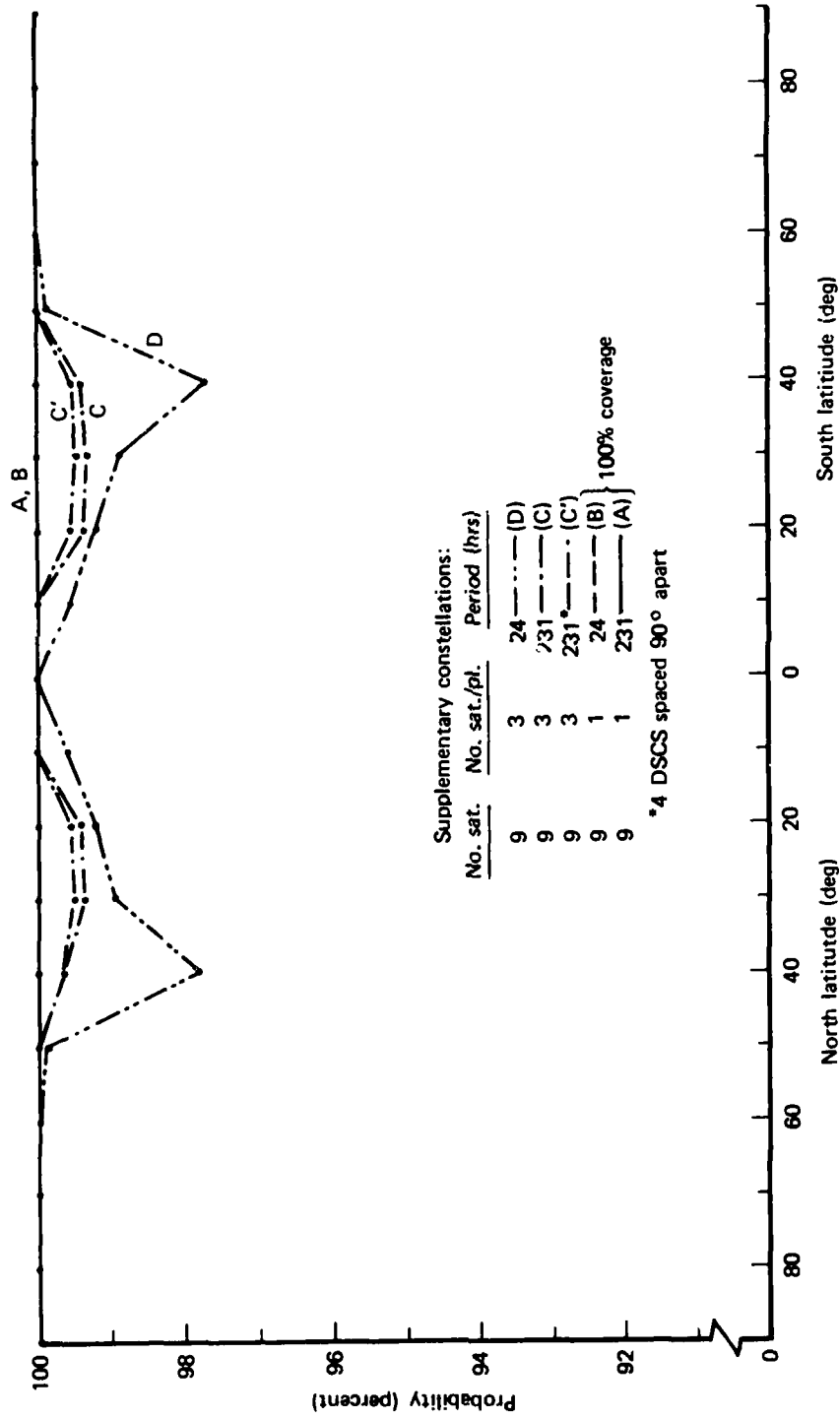Table 1 summarizes the worldwide coverage for constellation B.

Fig. 9—Probability of one or more satellites above 30° elevation angle for constellations including 4 DSCS: 13 satellites total
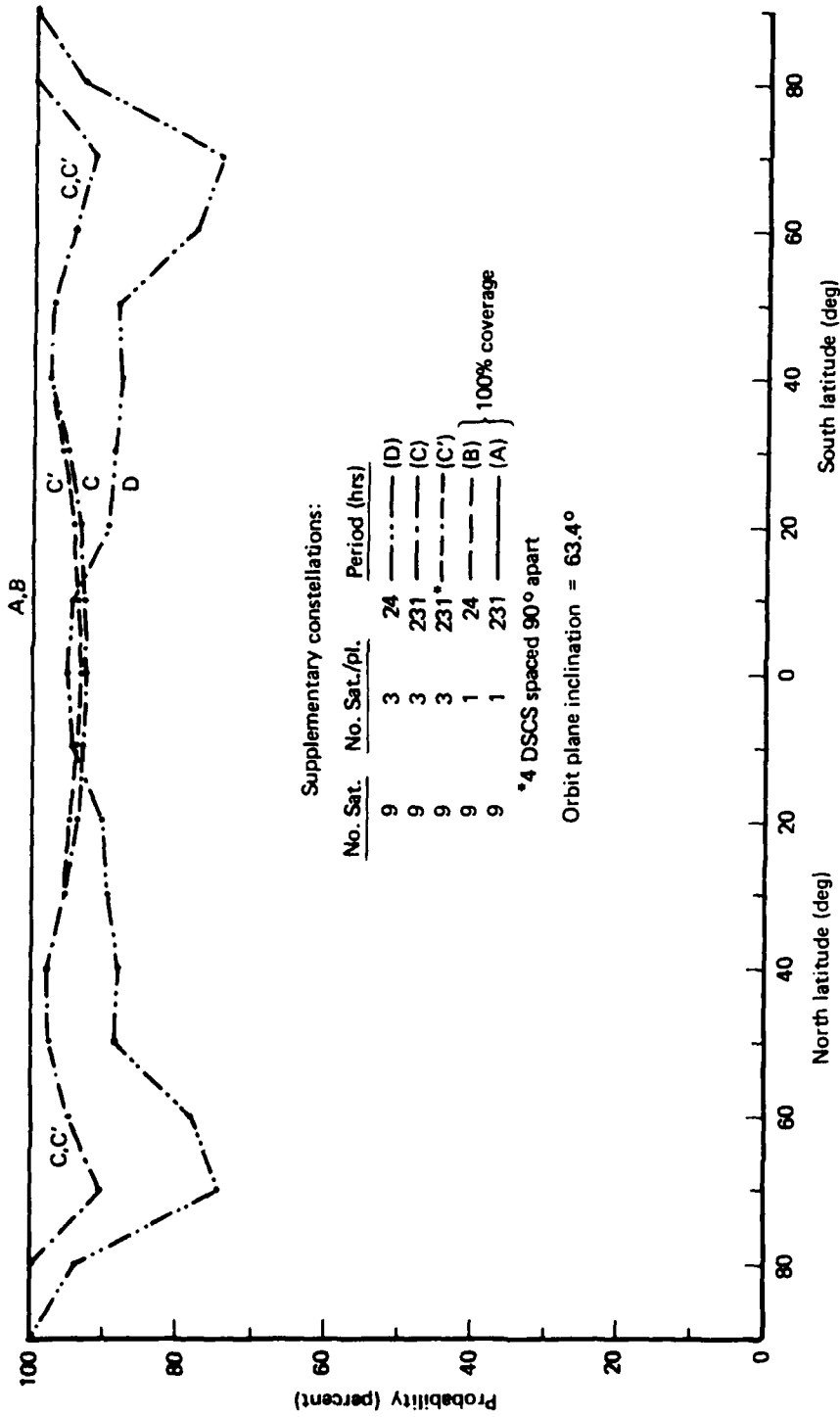
Fig. 10—Probability of two or more satellites above 30° elevation angle for constellations including 4 DSCS: 13 satellites total
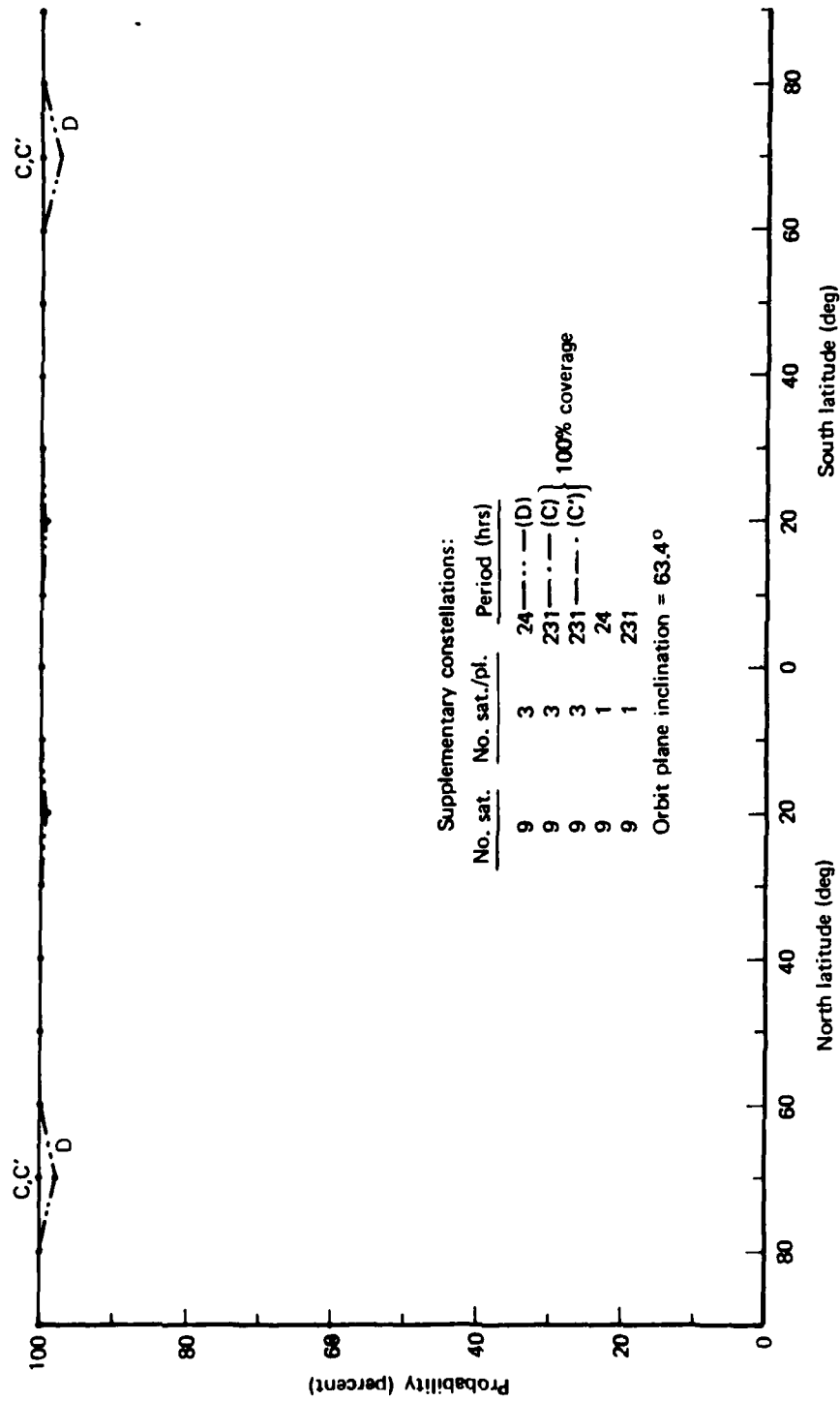
Fig. 11—Probability of two or more satellites above 20° elevation angle for constellations including 4 DSCS: 13 satellites total

Table 1

WORLDWIDE COVERAGE--CONSTELLATION B

CONSTELLATION PARAMETERS			MINIMUM COVERAGE (PERCENT)			
			One or more Satellites in View above Elevation Angle		Two or more Satellites in View above Elevation Angle	
No. of Satellites[a]	No. of Planes	Orbital	20°	30°	20°	30°
6	3	sync	99.2	92.1	71	33
6	3	5 x sync	97.1	92.2	80	47
6	6	sync	100	96.7	79	30
6	6	5 x sync	100	99.5	87	50
9	3	sync	100	97.8	97.5	74
9	3	5 x sync	100	99.3	100	80
9[b]	3	5 x sync	100	99.5	100	80
8	4	5 x sync	100	99.8	91.1	72.9

[a] Number of satellites needed in addition to the 4 DSCS.

[b] Uniform longitude spacing of DSCS.

IV. HEMISPHERE COVERAGE USING ELLIPTICAL ORBIT CONSTELLATIONS

Hemisphere coverage is best achieved using elliptical orbits and placing their apogees in the hemisphere of interest (say the northern hemisphere), at or near the maximum latitude that the satellite reaches (i.e., apogee latitude equal to the orbit plane inclination). This orbit orientation causes the time that the satellite is in the northern hemisphere to increase as the orbital eccentricity increases. As a result, the coverage in the northern hemisphere increases while the level of the residual coverage, i.e., coverage in the southern hemisphere, decreases.

Figure 12 shows the spacial orientation of a three-orbit plane constellation of nine satellites. The three planes are uniformly spaced (120° apart) in longitude and inclined 63.4°. The orbital eccentricity is 0.43.

The first satellite is initially located at the perigee of the first orbit. The spacing of the remaining satellites in the plane and between planes differs from the spacing that is optimum for the circular orbit constellations. In this case the satellites in each plane are equally spaced in time, which means that the central angles are not equal. For example, the initial true anomalies (central angles measured from orbital perigee) of the three satellites in the first plane are 0°, 152°, and 208° which correspond to a spacing of eight hours if the orbital period is 24 hours. The initial true anomalies of the first satellites (numbers 4 and 7) in planes 2 and 3 are, respectively, 87° and 127°. These angles correspond to time displacements from perigee of 24 : 9 (i.e., the period divided by the total number of satellites) and 2 x 24 : 9, respectively. The remaining satellites are then located at true anomalies which correspond to 8 hours and 16 hours relative to the first satellite in the plane. This initial equal time spacing, rather than equal angle spacing used for circular orbit constellations, maximizes the level of coverage.
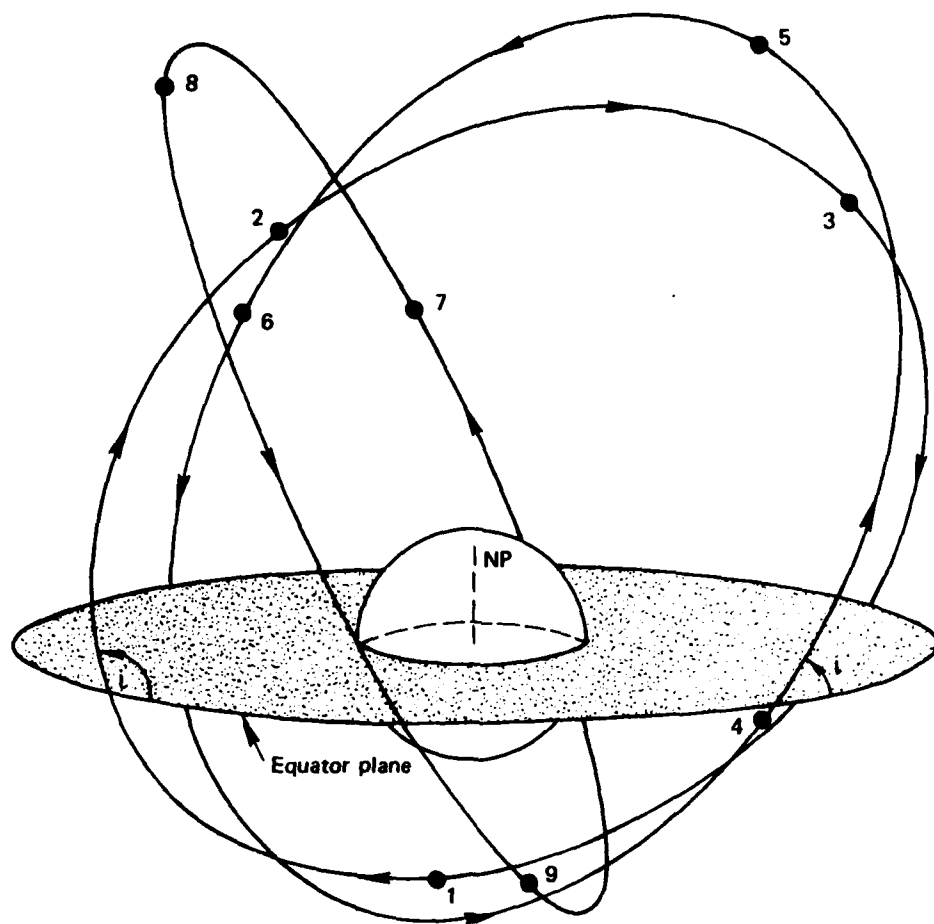
Fig.12 — Constellation with nine satellites in three elliptical inclined orbits

Figure 13 shows that a six-satellite constellation (three orbit planes with two satellites in each plane) with a period of 24 hours and inclined 63.4° to the equator will place one or more satellites in view of an earth-based user above 20° latitude if the elevation angle is 30° or more. For a 20° elevation angle the coverage is 100 percent above 10° latitude. Figure B-4 in Appendix B shows that the coverage is better for an orbital eccentricity of 0.63 than for either 0.43 or 0.83. Also, the coverage redundancy shown in Fig. 14 is best for this eccentricity. In fact, two or more satellites are in view above 40° latitude if the elevation angle is 30° or more.

By adding three more satellites to the above constellation (one satellite in each plane) the coverage becomes 100 percent in the northern hemisphere if the elevation angle is 20° or more. The coverage is 98 percent or more above 10° latitude for an elevation angle of 30° (see Fig. 15). In this case the coverage for an orbital eccentricity of 0.43 exceeds the coverage obtained for eccentricities of 0.63 and 0.83. This is shown in Fig. B-5 in Appendix B.

A comparison of Figs. 13 and 15 shows that the coverage in the southern hemisphere is increased from about 30 percent to 80 percent as a result of adding three satellites. Also, the coverage redundancy shown in Fig. 16 is significantly better in the southern hemisphere than that obtained using the six-satellite constellation (see Fig. 14).
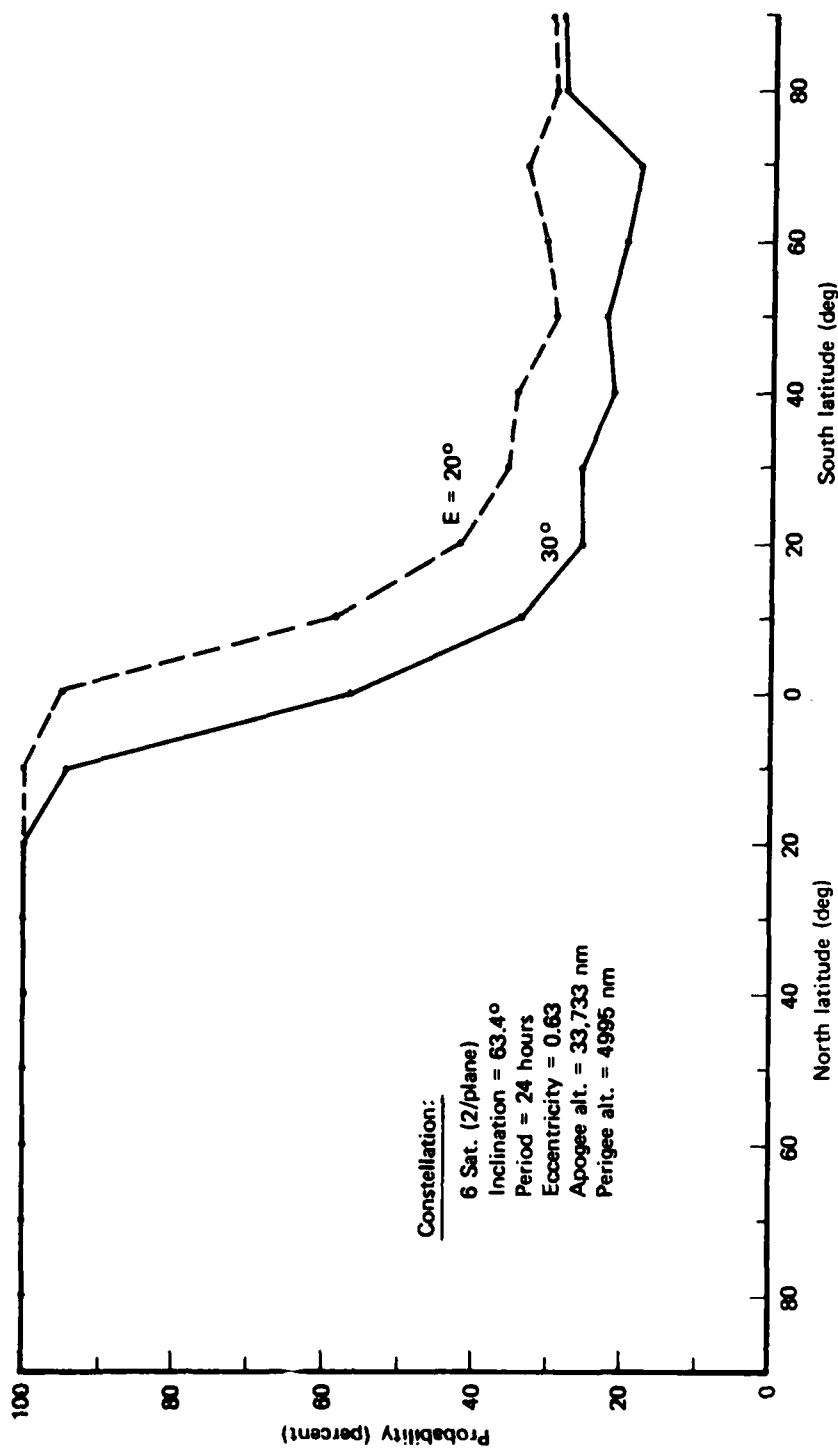
Table 2 summarizes the hemisphere coverage.

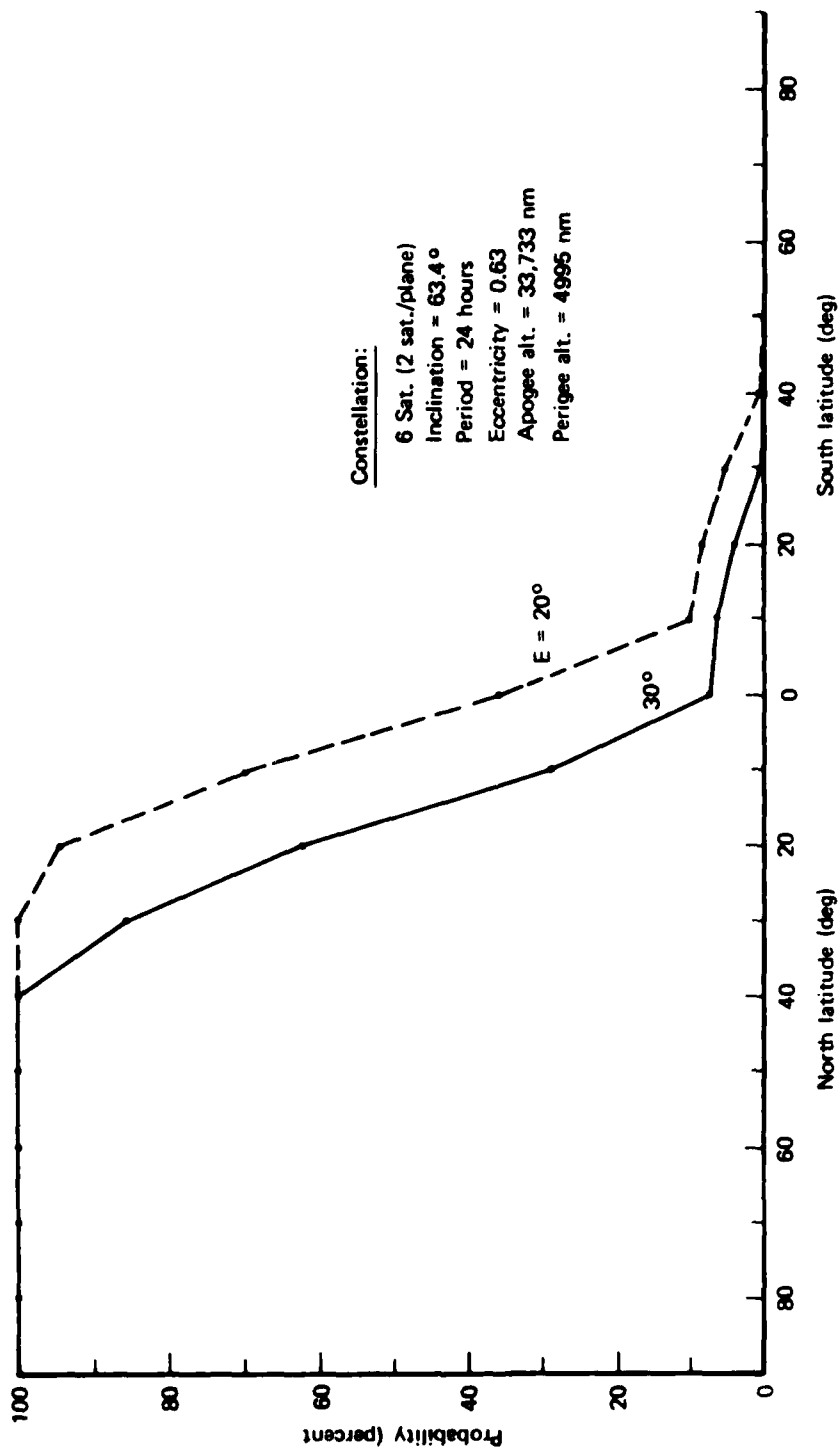Fig. 13—Probability of one or more satellites above elevation angle E: 6 satellites

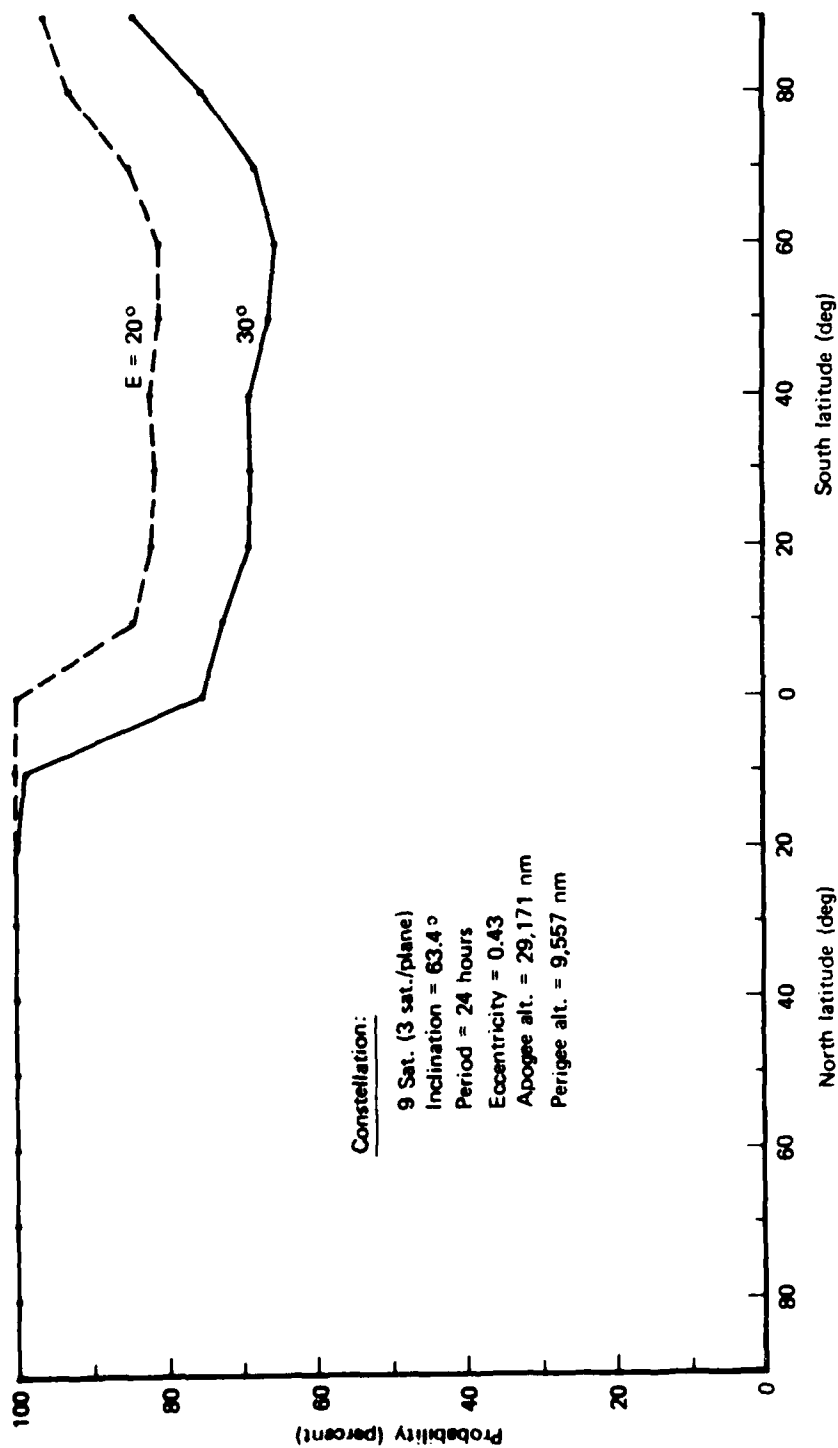Fig. 14—Probability of two or more satellites above a elevation angle E: 6 satellites

Constellation:

6 Sat. (2 sat./plane)
Inclination = 63.4°
Period = 24 hours
Eccentricity = 0.63
Apogee alt. = 33,733 nm
Perigee alt. = 4995 nm

Fig. 15—Probability of one or more satellites above elevation angle E: 9 satellites

Constellation:

9 Sat. (3 sat./plane)
Inclination = 63.4°
Period = 24 hours
Eccentricity = 0.43
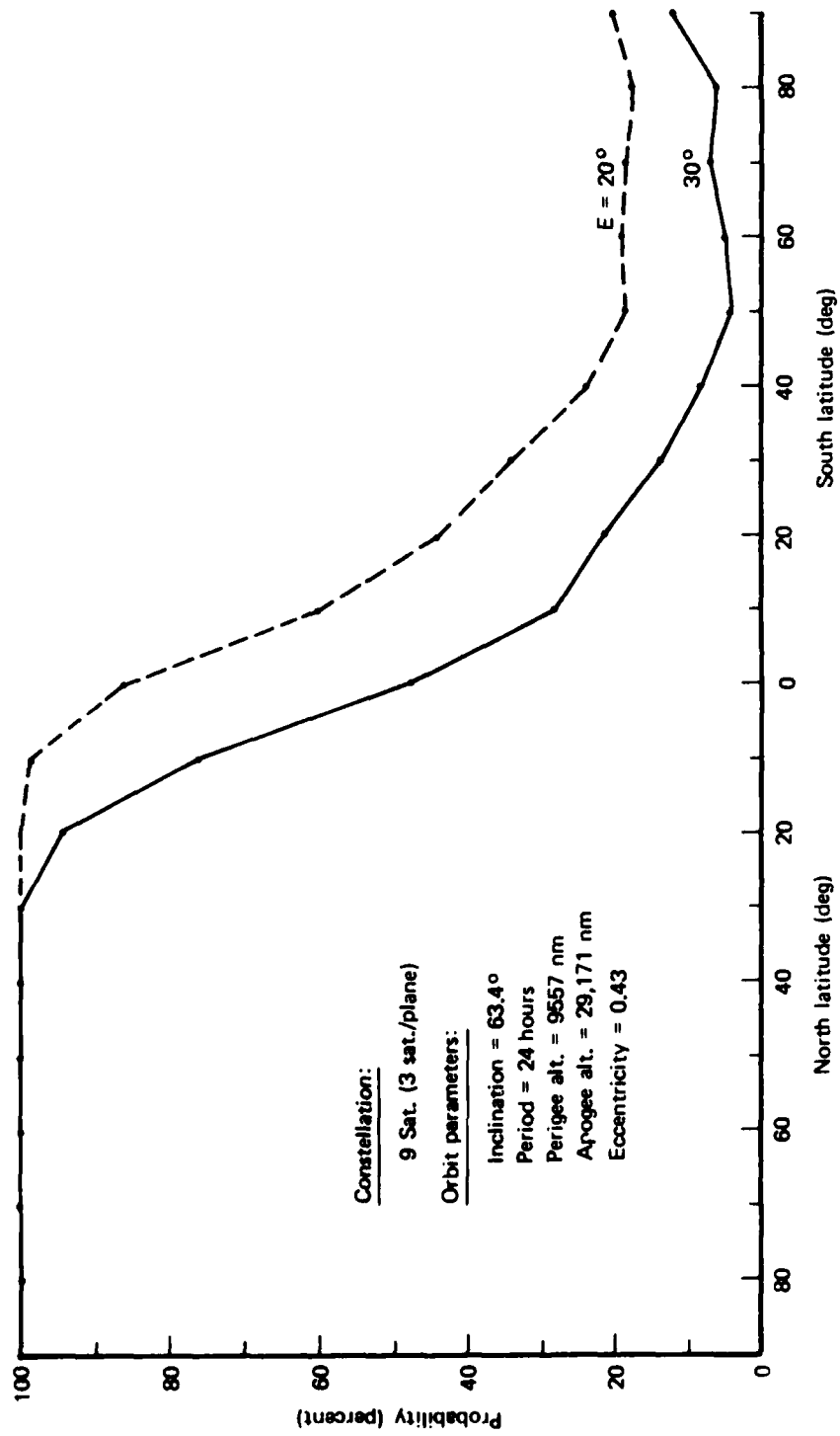Apogee alt. = 29,171 nm
Perigee alt. = 9,557 nm

Fig. 16—Probability of two or more satellites above elevation angle E: 9 satellites

Table 2

HEMISPHERE COVERAGE

CONSTELLATION PARAMETERS			MINIMUM COVERAGE (PERCENT)[a]			
			One or more Satellites in View above Elevation Angle[b]		Two or more Satellites in View above Elevation Angle[c]	
No. of Satellites	No. of Planes	Period (Hours)	20°	30°	20°	30°
6	3	24	95	56	36	7
9	3	24	100	75	86	48

[a]For all cases the minimum coverage occurs at 0° latitude.

[b]100 percent coverage occurs above 20° latitude.

[c]100 percent coverage occurs above 40° latitude.

V.   HEMISPHERE AND EQUATORIAL REGION COVERAGE

Constellations that consist of elliptical, inclined orbits are
optimal for hemisphere coverage. However, 100 percent coverage near
the equator is difficult to achieve without satellites in the
equatorial plane. In order to obtain coverage in the equatorial
region as well as hemisphere coverage, hybrid constellations con-
sisting of both elliptical, inclined orbits and circular, equatorial
orbits are investigated.

Figure 17 shows a typical synchronous altitude, hybrid con-
stellation. It consists of nine satellites in inclined, elliptical
orbits plus four satellites in equatorial, circular orbits. This
constellation gives 100 percent worldwide coverage (see Fig. 9).
If three of the satellites in elliptical orbits are removed (one
from each plane), the ten-satellite constellation yields the coverage
shown in Fig. 18.

By increasing the number of inclined orbit planes to four and
putting only one satellite in each plane it is possible to obtain
the coverage shown in Fig. 19 with only eight satellites. The basic
coverage (i.e., one or more satellites in view) north of 30° south
latitude is 100 percent, the same as for the ten-satellite constella-
tion. However, the residual coverage at the higher southern
latitudes and the coverage redundancy for all latitudes is better if
the ten-satellite constellation is used.

Orbits I, II, III

$e = 0.43$

$h_p \approx 9,556$ nm

$h_a = 29,171$ nm
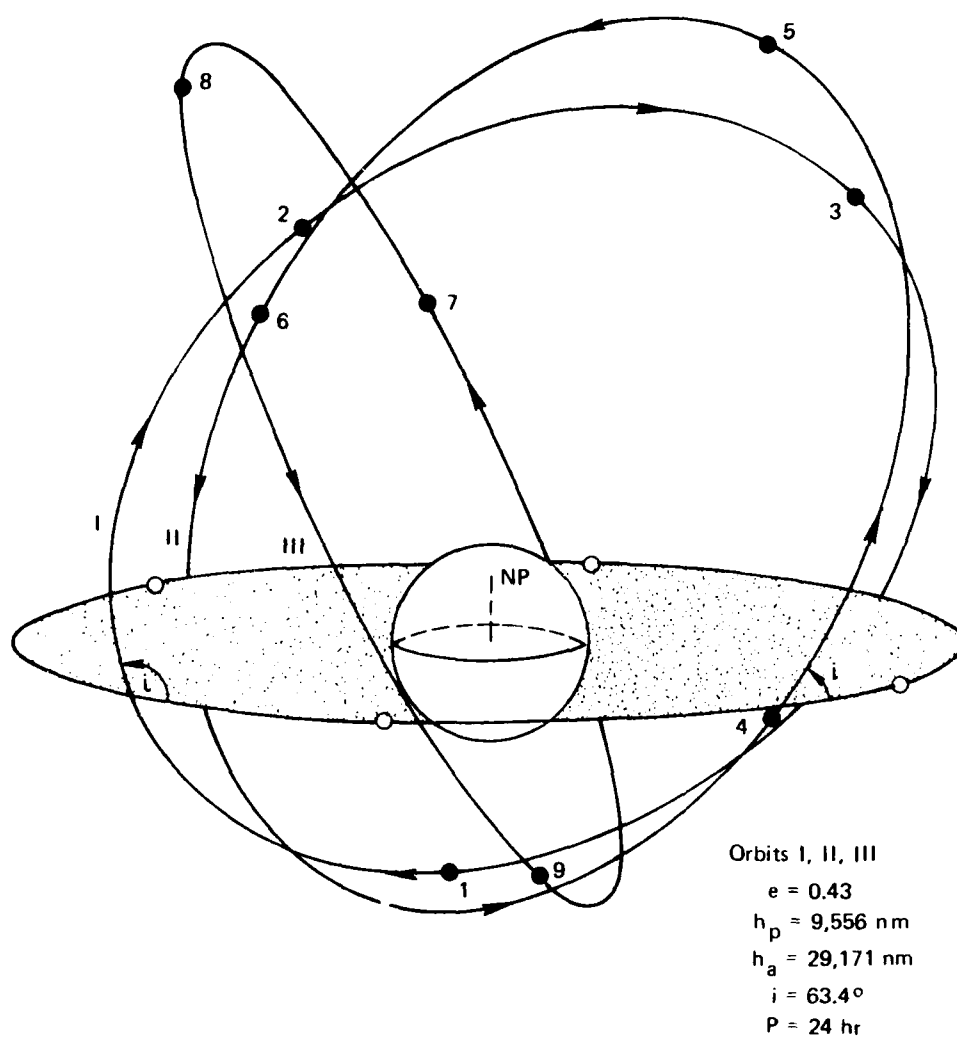
$i = 63.4°$

$P = 24$ hr

Fig. 17 — DSCS supplemented with 9 satellites: Northern hemisphere
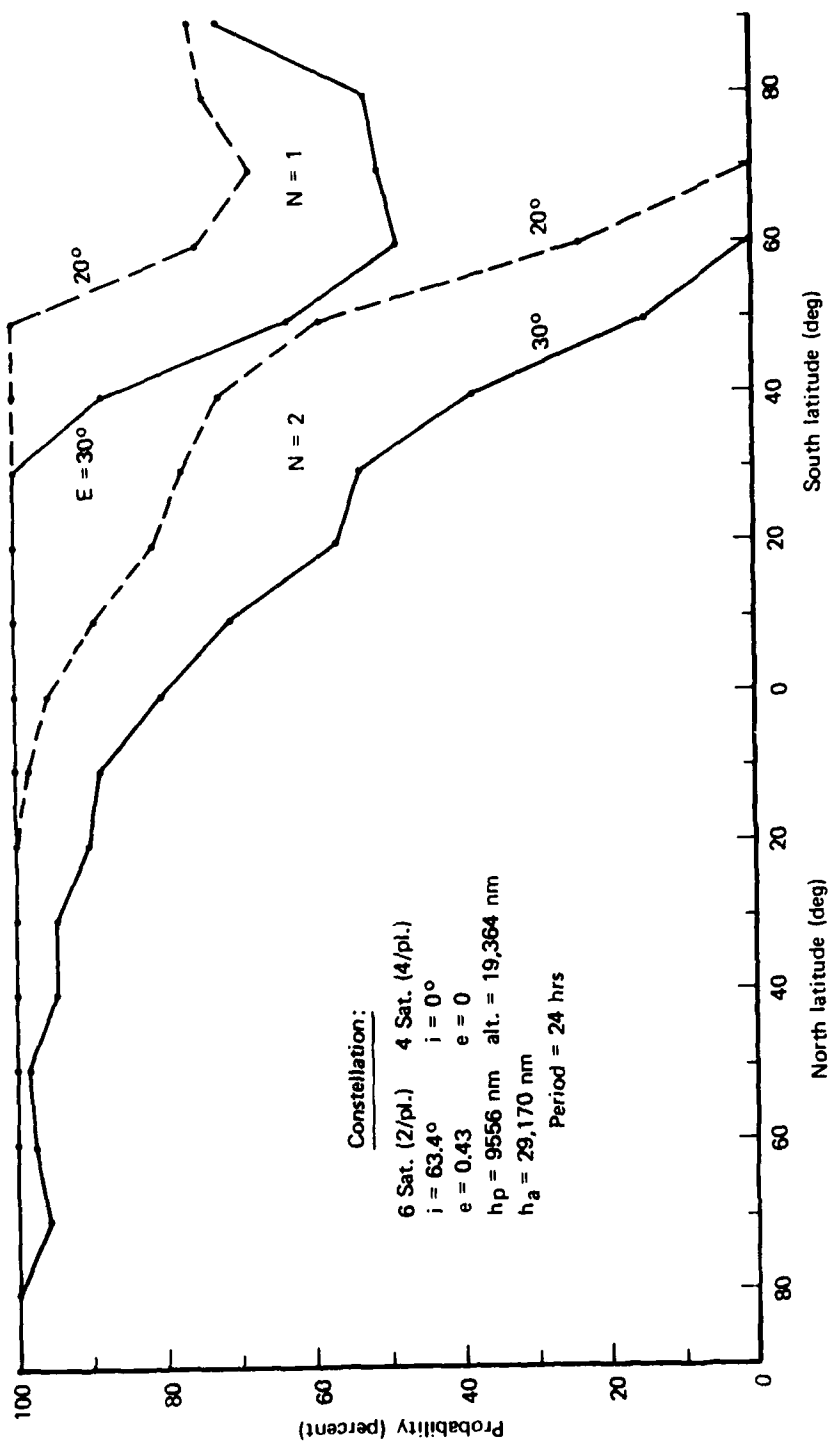and equatorial region coverage

Fig. 18—Probability of N or more satellites above elevation angle E: 10 satellites
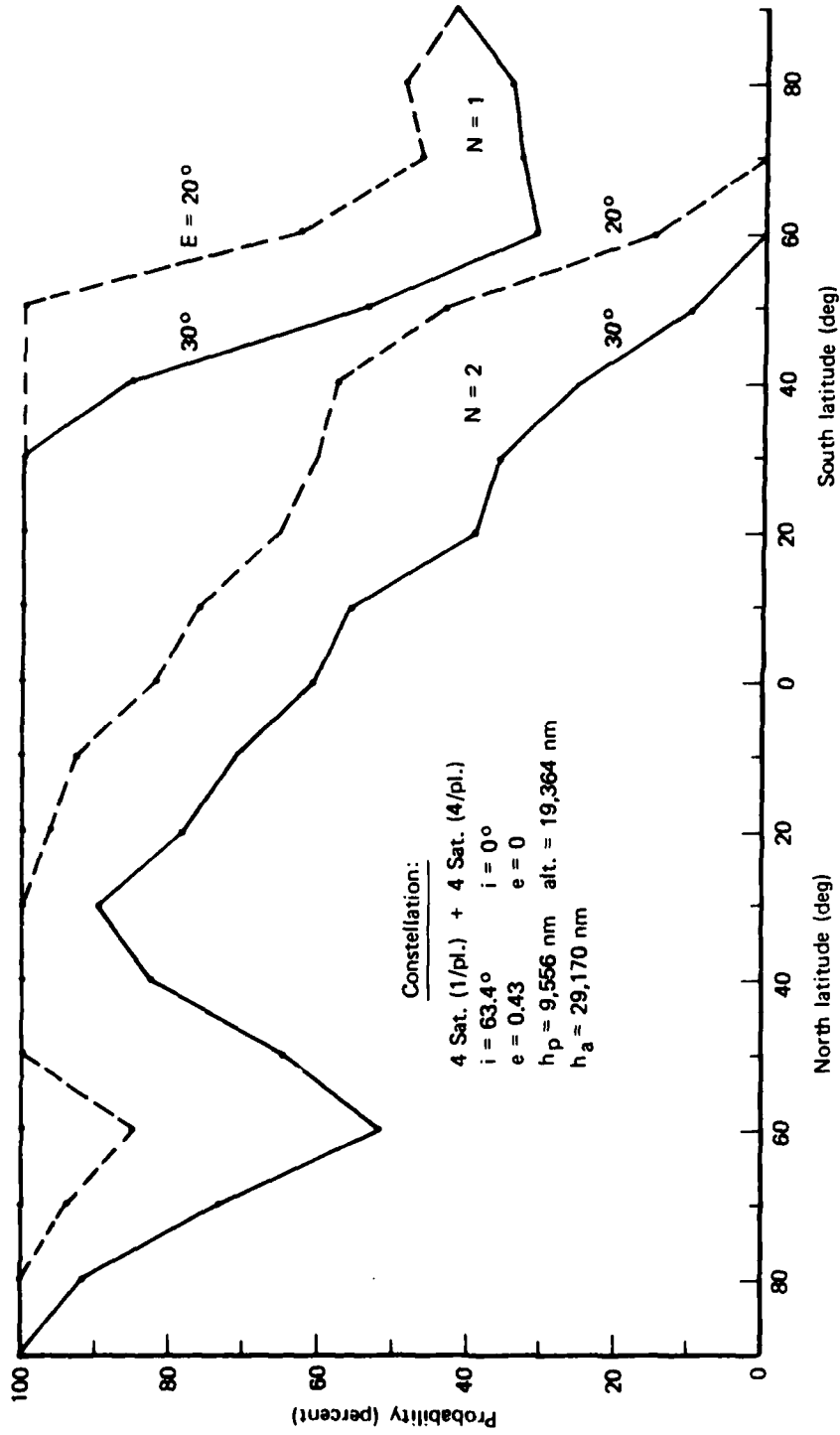
Fig. 19—Probability of N or more satellites above elevation angle E: 8 satellites

Appendix A

EFFECT OF CONSTELLATION PARAMETER VARIATION ON COVERAGE

The effect on coverage that is caused by varying the constella-
tion parameters is shown in Figs. A-1 through A-6. The four
parameters varied are: constellation longitude, satellite true
anomaly, number of satellites, and number of orbit planes.

The variation in coverage caused by parameter variation will be
different for different constellations even though the parameter
variation is the same. For example, a 20° change in the initial
longitude of the constellation will have less effect on coverage
if the altitude of the constellation is increased. Also, it is
ii ortant to note that the parameters of the DSCS constellation are
not changed, only those of the constellations used to supplement
the DSCS.

Figure A-1 shows the change in coverage for a longitude shift
of the nine-satellite constellation supplementing the DSCS. The
three orbit planes contain three satellites each and they are
separated by 120° on longitude.

Initially the longitude of the ascending node* of the first
orbit plane is 0°. Also, the satellites are separated by 120° in-
plane.** The maximum difference in the coverage is about 0.4 percent
at 20° north latitude.

The effect of the initial positions of all the satellites in the
supplementary constellation on coverage can be significant. The
curve in Fig. A-2 shows the coverage for 0° initial true anomaly
to be significantly less than for the other values of the initial

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*The ascending node is the node with the equator plane through
which the satellite passes south to north.

**Initially, the first satellite in the first plane is above
the equator, the fourth satellite (first in the second phase) is
advanced 40° in-plane, and the seventh satellite (first satellite
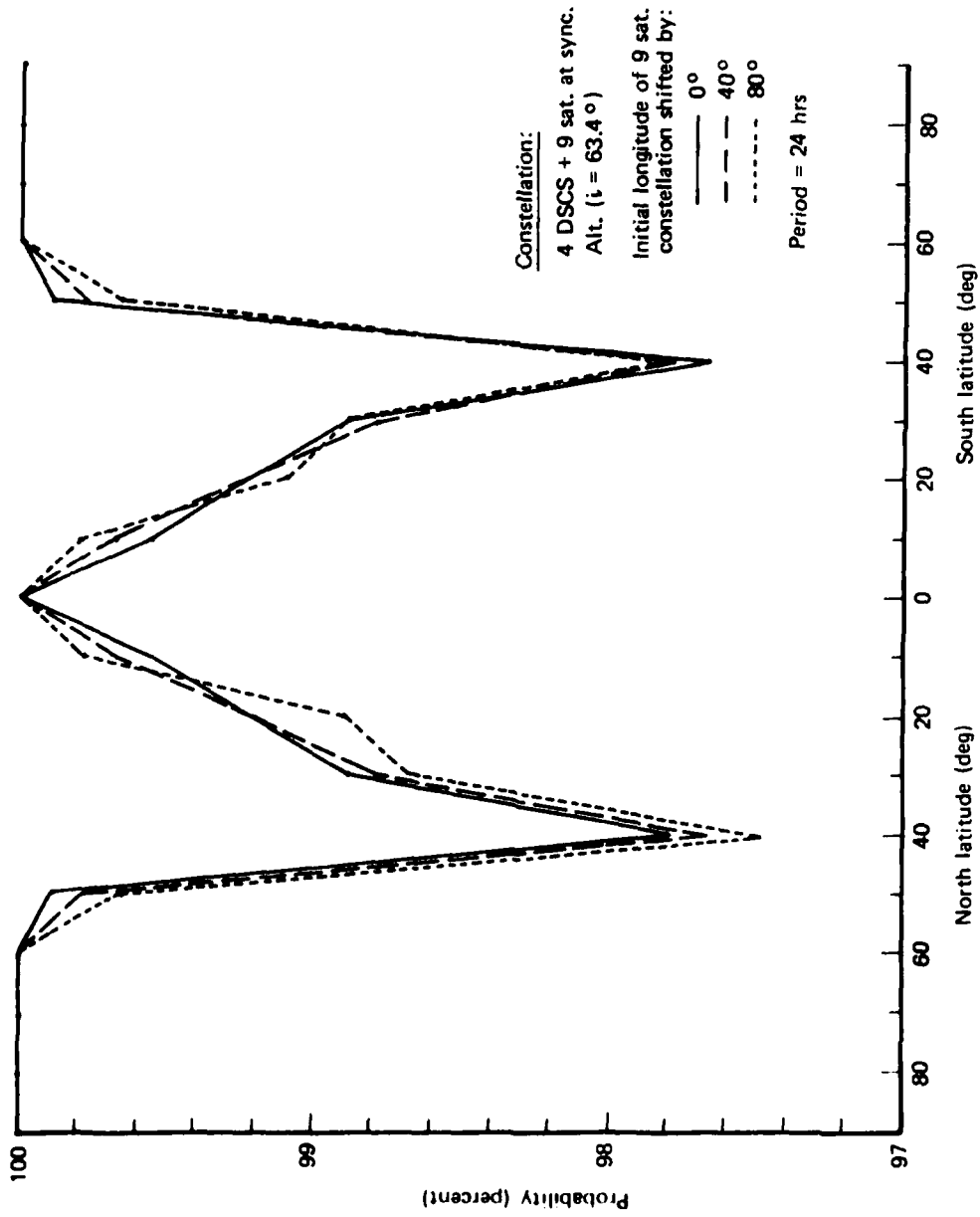in the third plane) is advanced 80° in-plane.

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Fig. A-1 — Probability of one or more satellites above 30° elevation angle: initial longitude of 9 satellite constellation varied
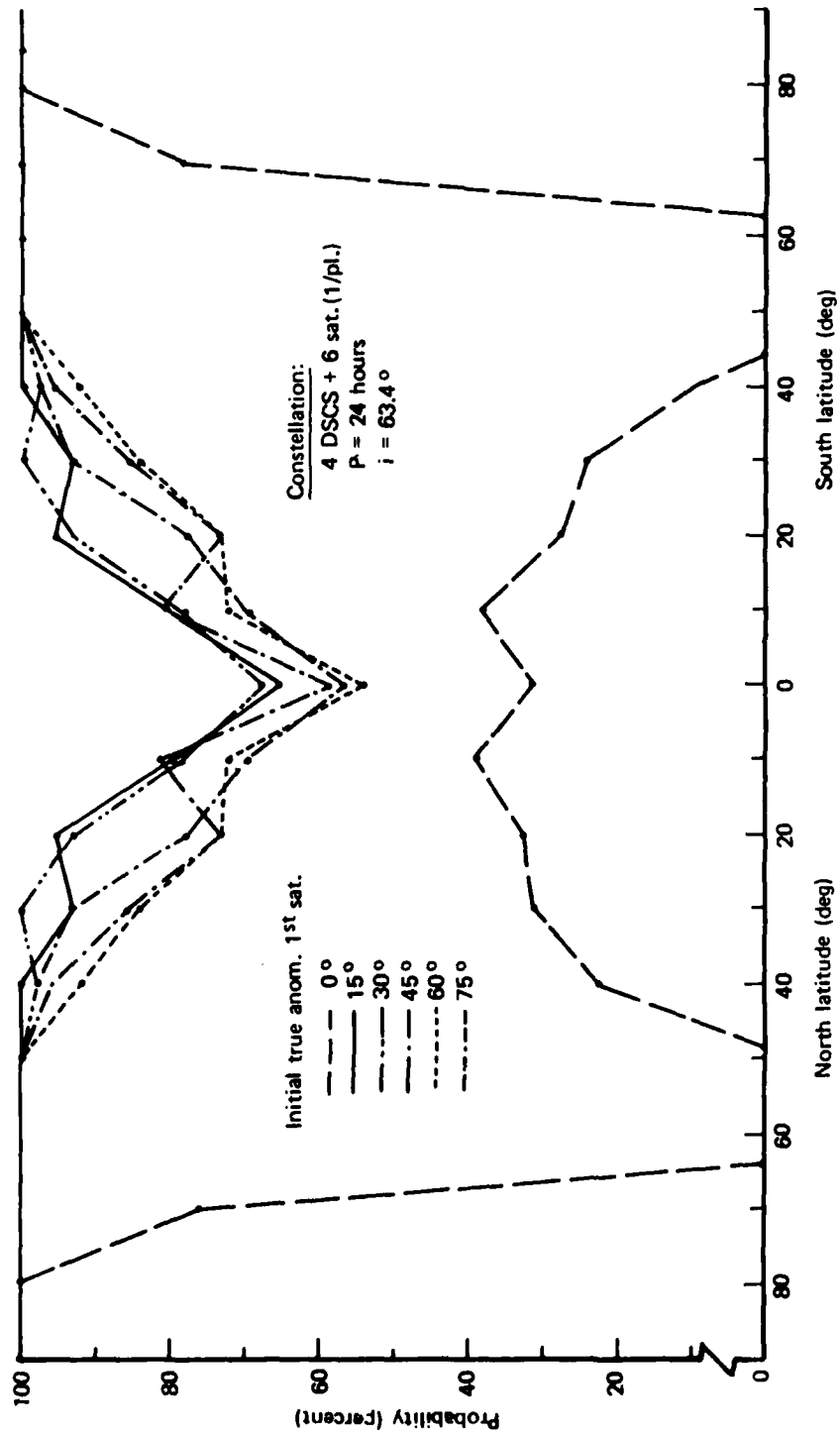
Fig. A-2—Probability of one or more satellites above 30° elevation angle: initial true anomaly

true anomaly. This much lower probability of coverage occurs be-
cause the equal longitude spacing of the orbit planes (every 60°) and
the 60° in-plane advance of satellites from plane to plane causes
satellites one and four to start at the same location and return
once every orbital period. Thus, the initial relative positions of
the satellites must be carefully chosen. Note that the coverage is
significantly improved when the satellites are advanced 15° in their
orbits. This happens because no two satellites start at the same
position. As all satellites are further advanced in steps of 15°,
the maximum difference in coverage is about 1.5 percent. The optimum
value of the initial true anomaly is probably between 15° and 30°.

Figure A-3 shows the coverage obtained if the DSCS is supplemented
by constellations of six and nine satellites in three orbit planes
inclined 63.4° to the equator. Over the range of latitude ± 50° the
coverage is improved by about 6 percent if three satellites are
added (one per plane) to the six-satellite constellation.

The effect of increasing the number of orbit planes on coverage
is shown by Figs. A-4 and A-5. In Fig. A-4 the coverage is shown
for a supplementary six-satellite constellation using three orbit
planes and six orbit planes. The improvement in coverage that re-
sults with this increase in the number of orbit planes is about 6
percent over the latitude range ± 60°. Figure A-5 shows the effect
on coverage of changing the number of orbit planes from three to
six while using a constellation of six satellites in elliptical, in-
clined orbits. With the goal of hemisphere coverage in mind, the
three orbit plane constellation gives better coverage. However, the
residual coverage in the southern hemisphere is significantly better
if the number of orbit planes are increased to six.

Figure A-6 shows the coverage change that occurs if both the
number of satellites and the number of orbit planes are increased.
It is clear that a constellation of eight satellites in eight orbit
planes will not give 100 percent hemisphere coverage for an eleva-
tion angle of 30°. A hybrid constellation consisting of elliptical,
inclined orbits and circular, equatorial orbits is preferred. This
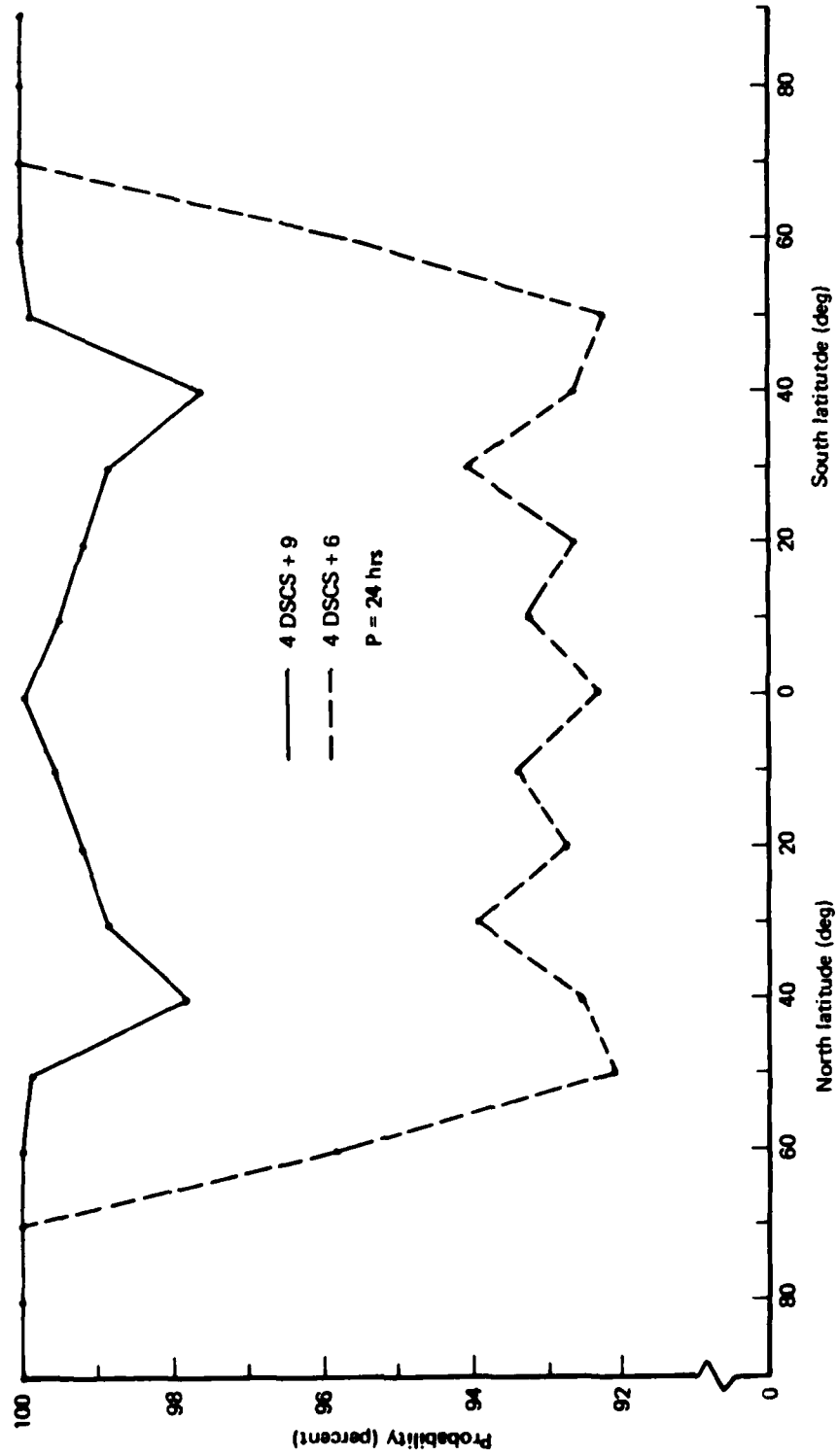
Fig. A-3—Effect of number of satellites on probability of one or more satellites above 30° elevation angle
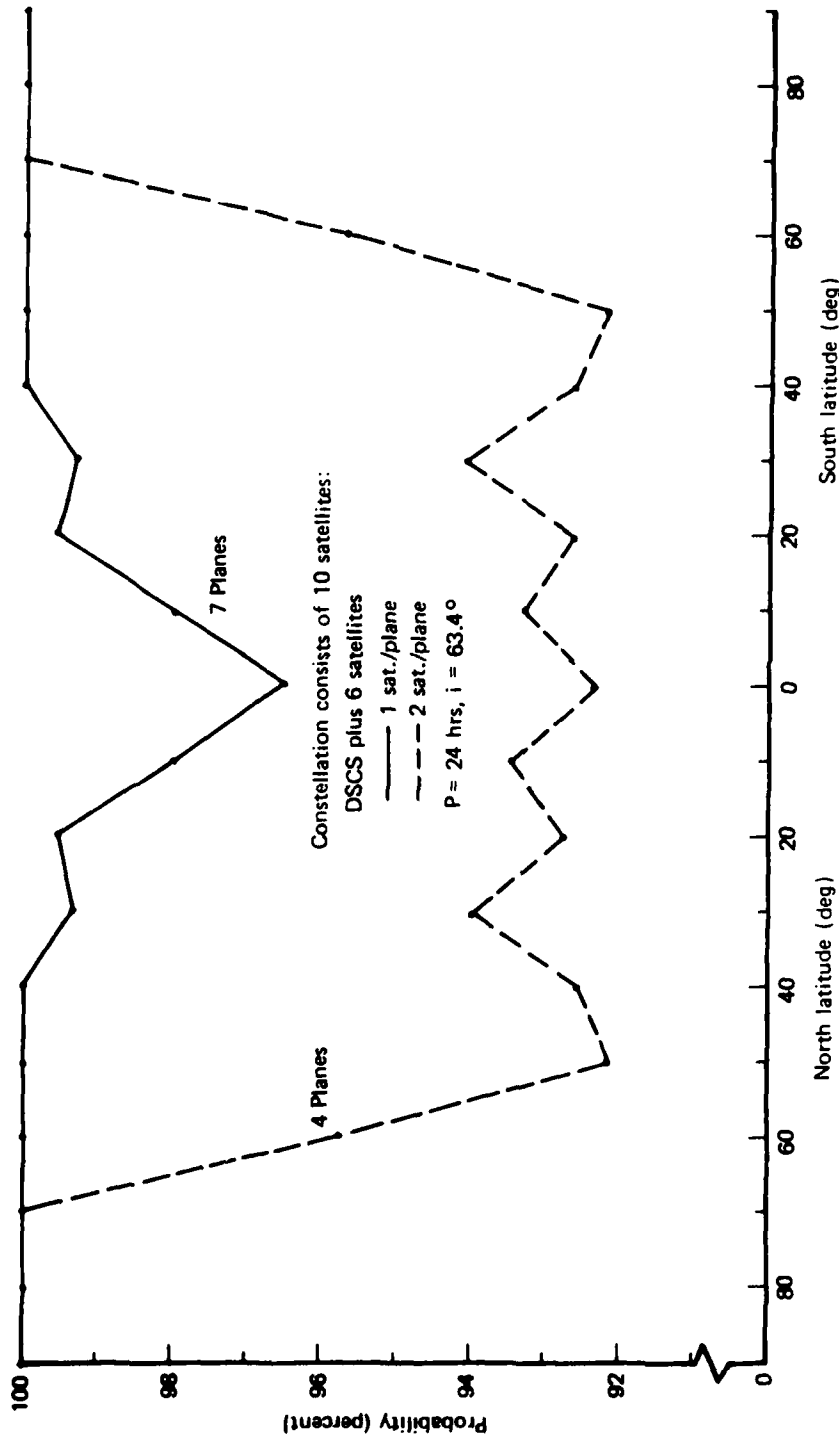
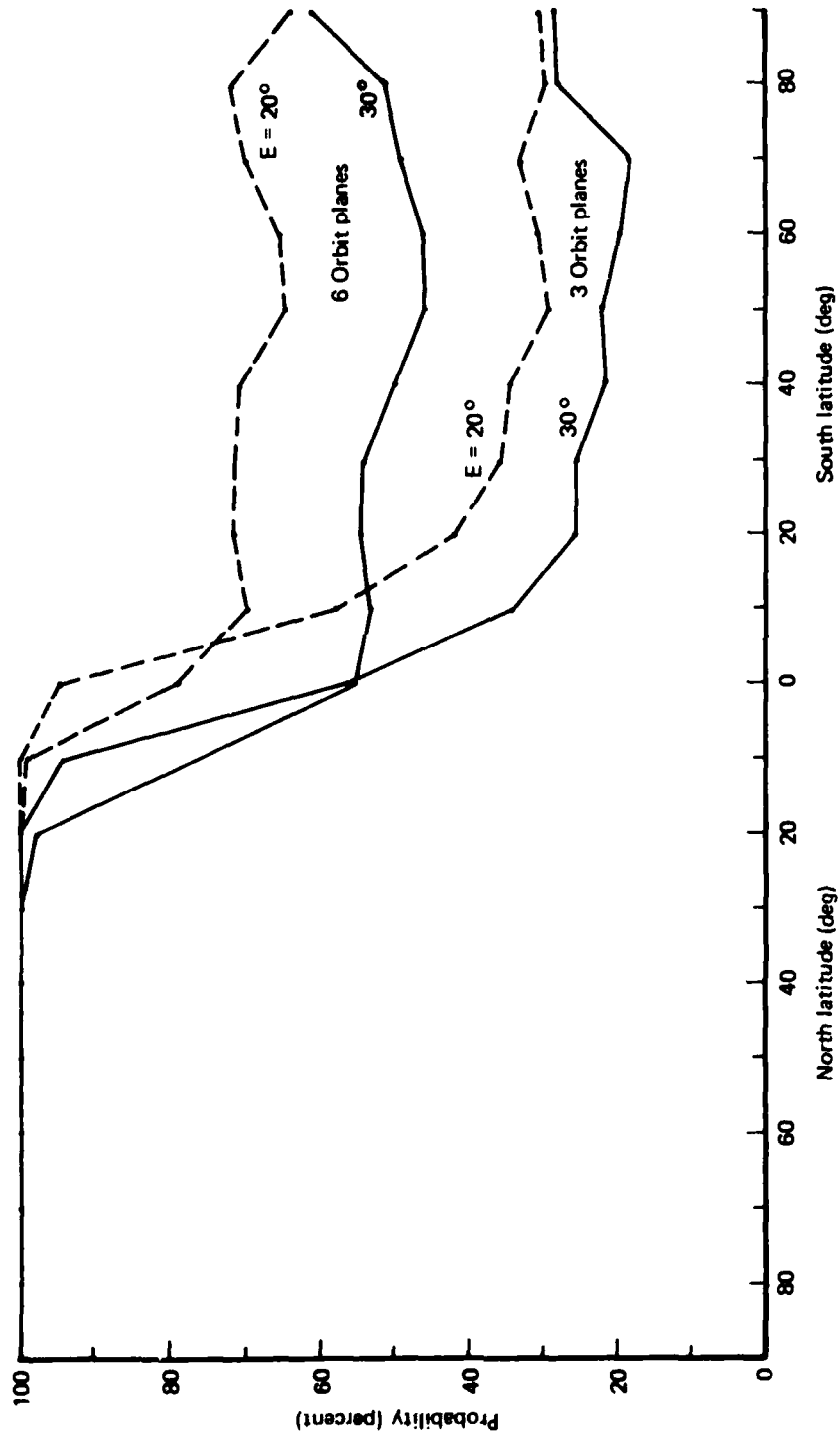Fig. A-4—Effect of number of orbit planes on probability of one or more satellites above 30° elevation angle

Fig. A-5—Probability of one or more satellites above elevation angle E: 6 satellites
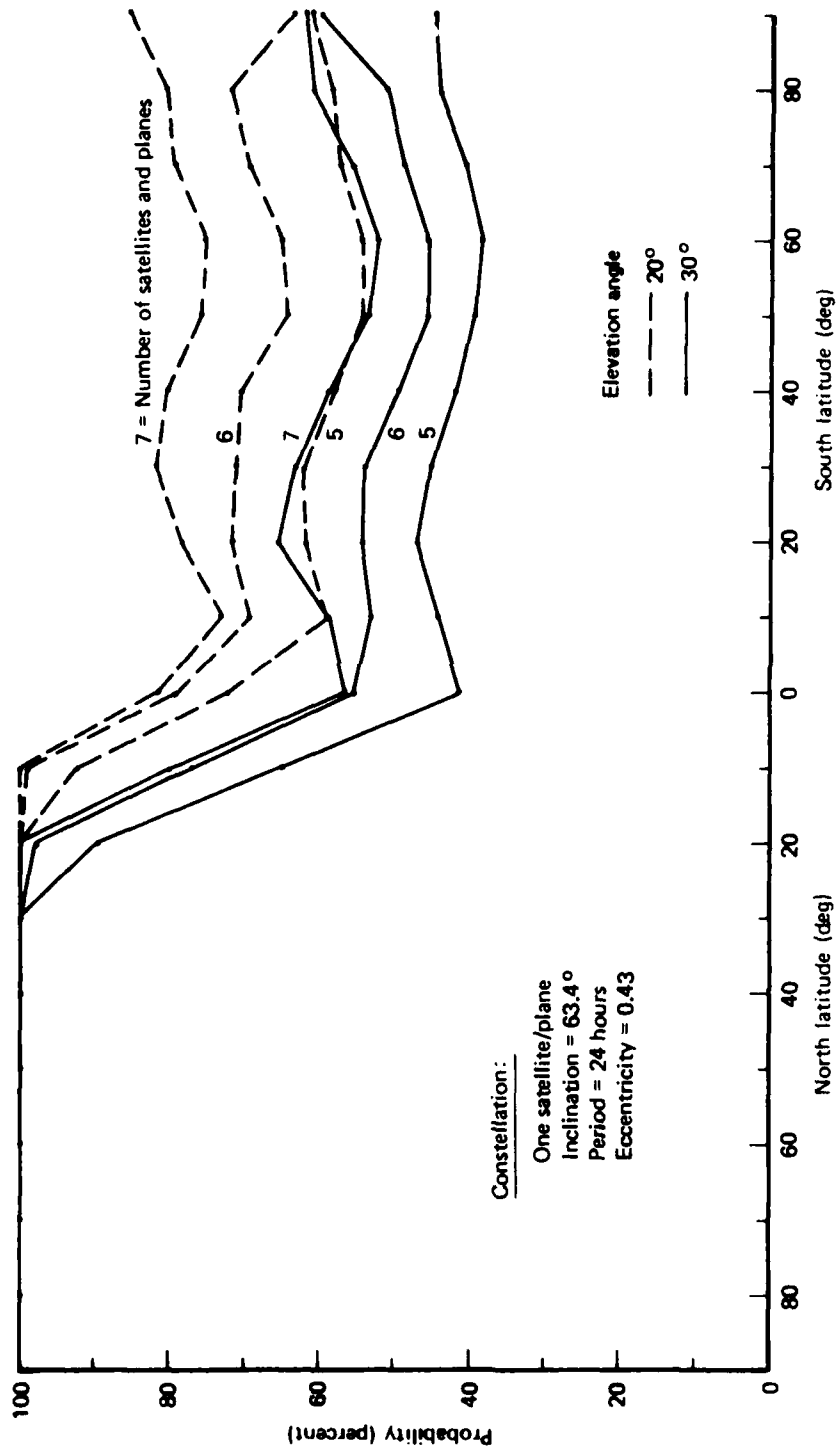
Fig. A-6—Effect of number of satellites and number of orbit planes on probability
of one or more satellites above elevation angle E

is indicated in Fig. 19 where a hybrid constellation of eight
satellites gives hemisphere coverage plus equatorial region coverage.

SUMMARY

- The initial longitude of the constellation does not
  significantly affect coverage.
- The initial relative true anomalies of the satellites
  can significantly decrease the coverage unless they are
  carefully chosen.
- Coverage increases as the number of satellites increases.
- The number of orbit planes can be varied, while using a
  fixed number of satellites, to enhance coverage for
  certain ranges of latitudes.
- Hybrid constellations are best if both hemisphere and
  equatorial region coverage are desired.

Appendix B
EFFECT OF ORBIT PARAMETER VARIATION ON COVERAGE

The effect of orbit parameter variation on coverage is shown in Figs. B-1 through B-5. The three orbit parameters varied are: altitude, inclination, and eccentricity.

Figure B-1 shows the change in coverage that results if the altitude of the nine satellites used to supplement the DSCS is raised from sync to 5 x sync. The maximum improvement in coverage of about 1.8 percent occurs at $\pm$ 40° latitude.

The coverage change for a much smaller variation of the orbital altitude is shown in Fig. B-2. The altitude of the nine satellites supplementing the DSCS was raised to increase the orbital period to 25 hours and then lowered to reduce the period to 23 hours. The maximum loss in coverage is about 0.6 percent in either case.*

The effect on coverage that results when the orbit plane inclination is changed is shown in Fig. B-3. As the inclination decreases, the satellites spend less time at high latitudes and consequently the coverage probability is reduced. The optimal inclination for the constellation supplementing the DSCS appears to be about 65°.

Figures B-4 and B-5 show the effect of orbital eccentricity change on coverage. The constellations consist of only elliptical orbits that are inclined 63.4°. For the six-satellite constellation (Fig. B-4), the northern hemisphere coverage degrades more rapidly with a decrease in the eccentricity than it does for the nine-satellite constellation shown in Fig. B-5. Also, the use of nine satellites causes the minimum latitude for which there is complete coverage to decrease toward the equator by about 10°. For zero eccentricity, the coverage at the equator is significantly better for the nine-satellite constellation.

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*A small change in the orbital period from 24 hours causes the trace of the satellite subpoint to shift in longitude. This could enhance the system's survivability.
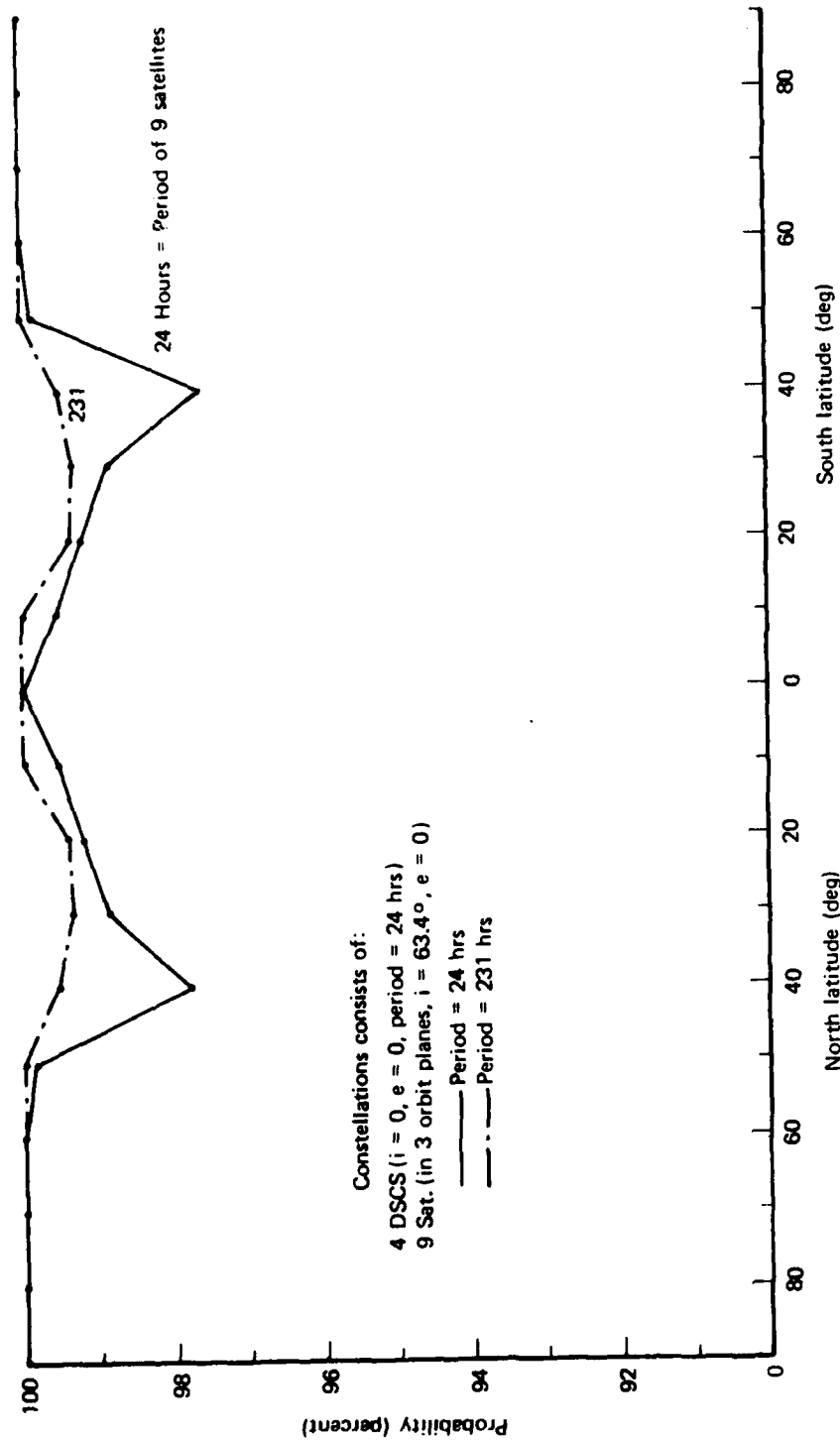
Fig. B-1—Effect of orbital altitude on probability of one or more satellites above 30° elevation angle
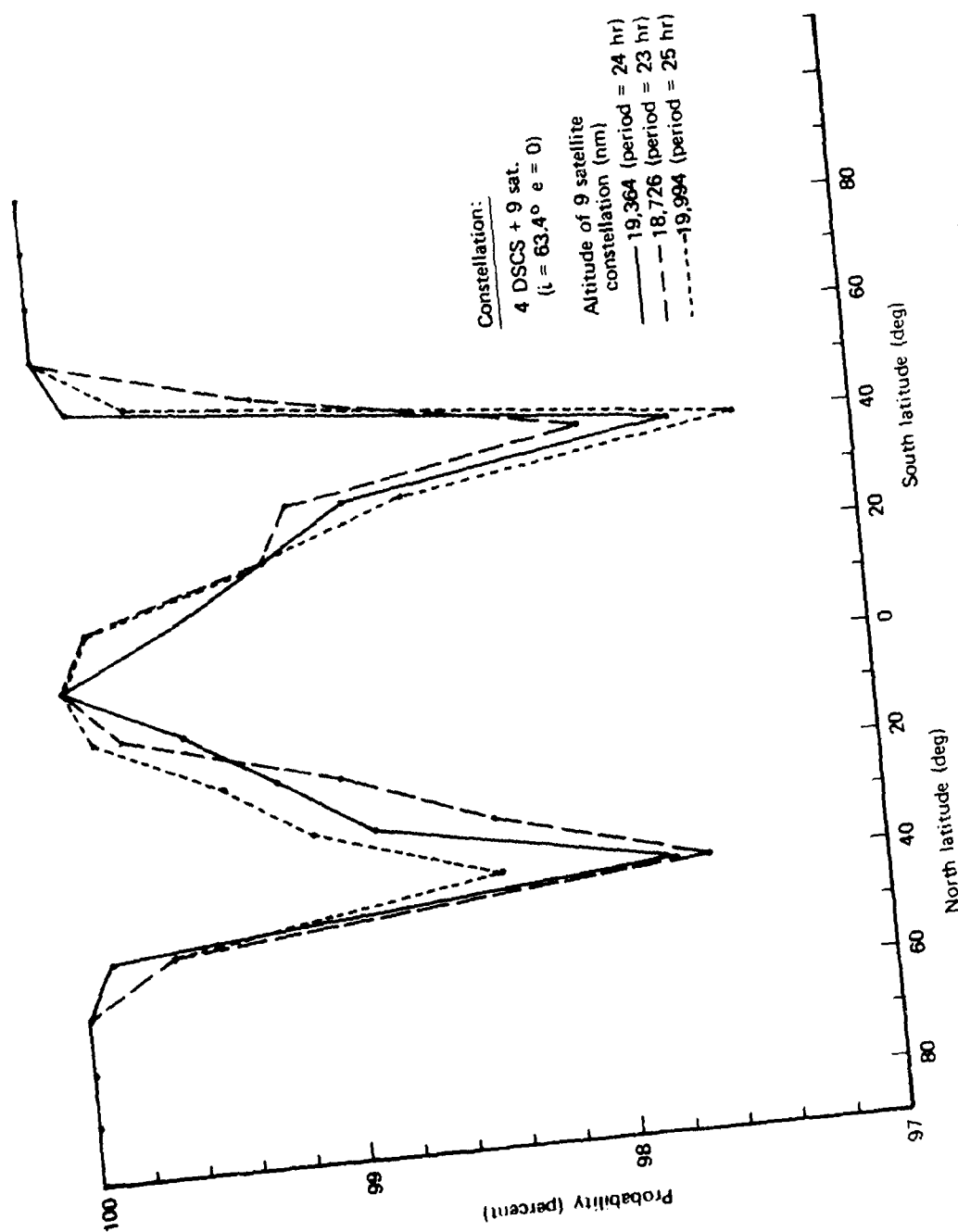
Fig. B-2—Probability of one or more satellites above 30° elevation angle:
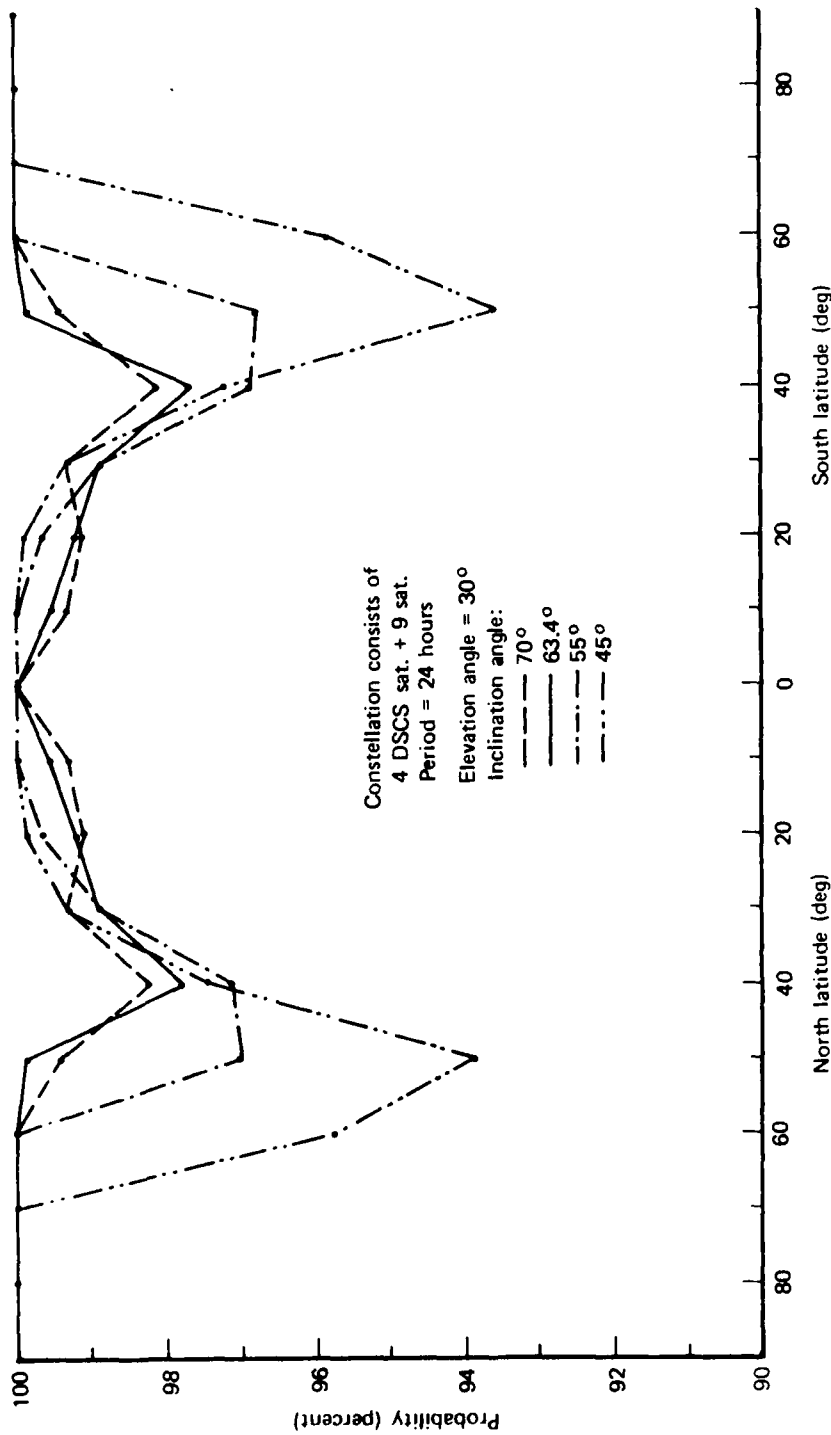altitude of 9-satellite constellation varied

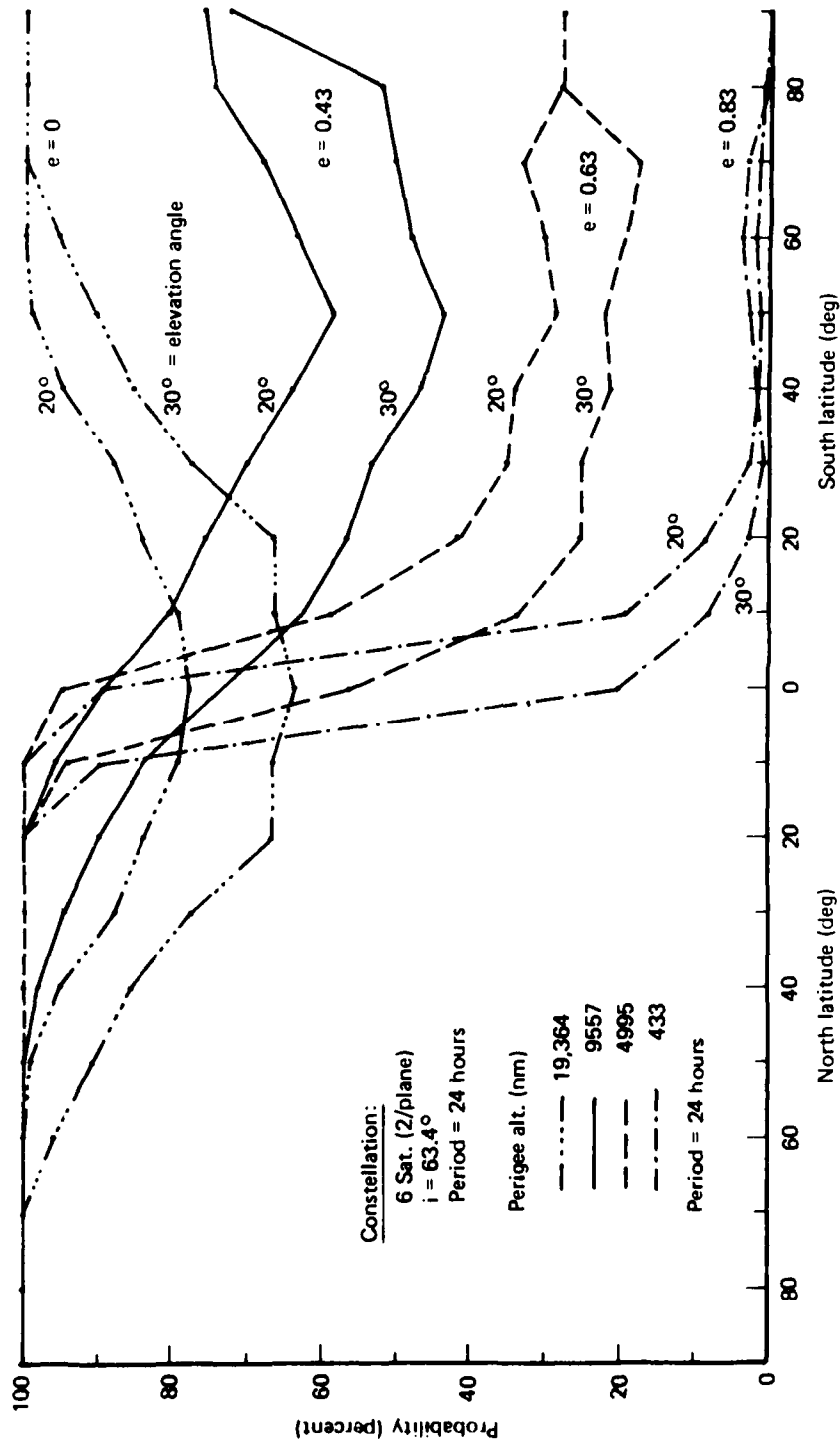Fig. B-3—Effect of orbit plane inclination on probability of one or more satellites above 30° elevation angle

Fig. B-4—Effect of orbital eccentricity on probability of one or more satellites above elevation angle E: 6 satellites total
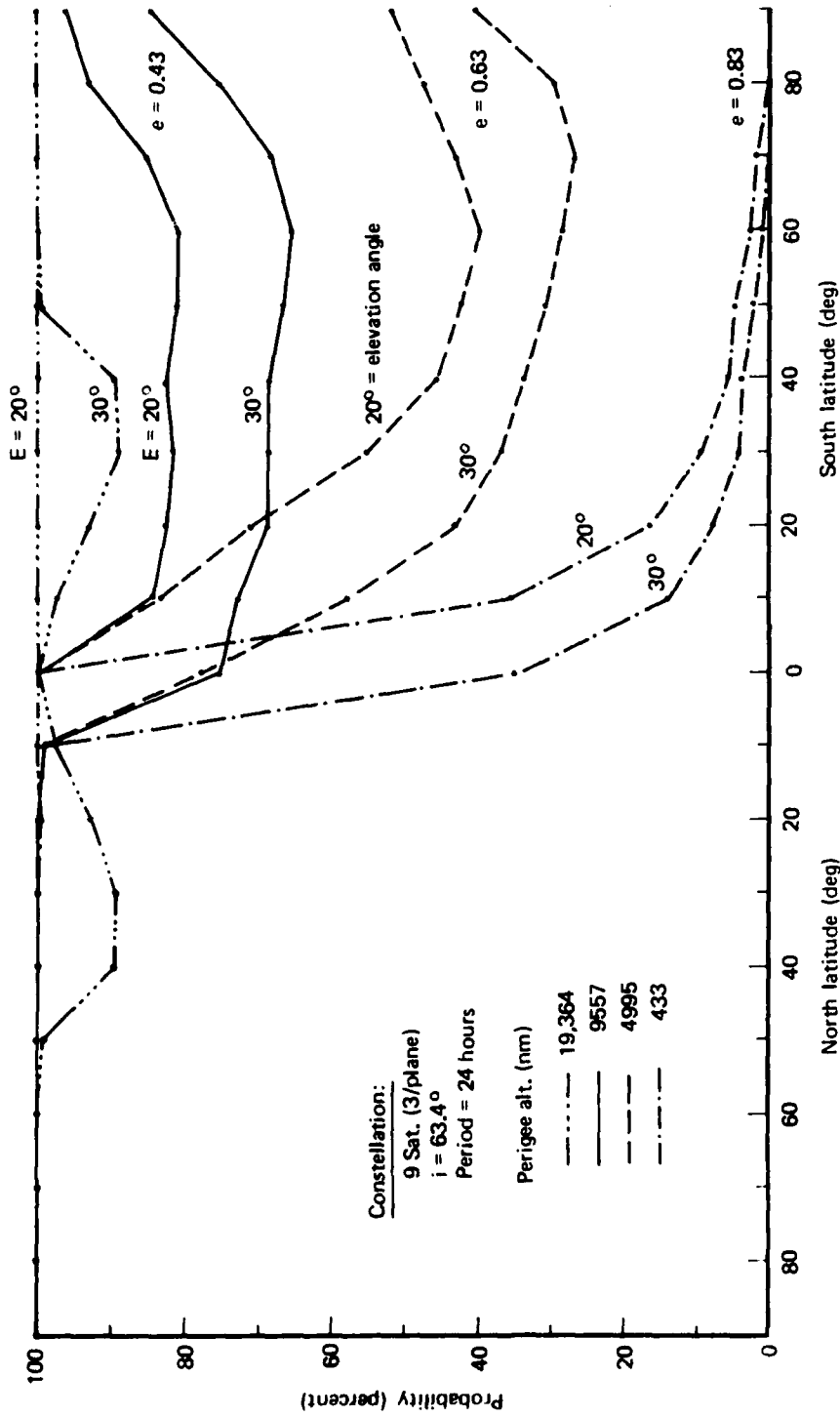
Fig. B-5—Effect of orbital eccentricity on probability of one or more satellites above elevation angle E

SUMMARY

- Increasing the orbital altitude (period) improves the coverage probability.
- Small changes in the orbital altitude will not significantly affect the level of coverage but will cause the earth trace of the satellite subpoint to shift in longitude.
- Orbit plane inclination can be varied to maximize coverage over specified ranges of latitude.
- Orbital eccentricity can be varied to maximize coverage in the southern hemisphere while maintaining 100 percent coverage in the northern hemisphere.

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